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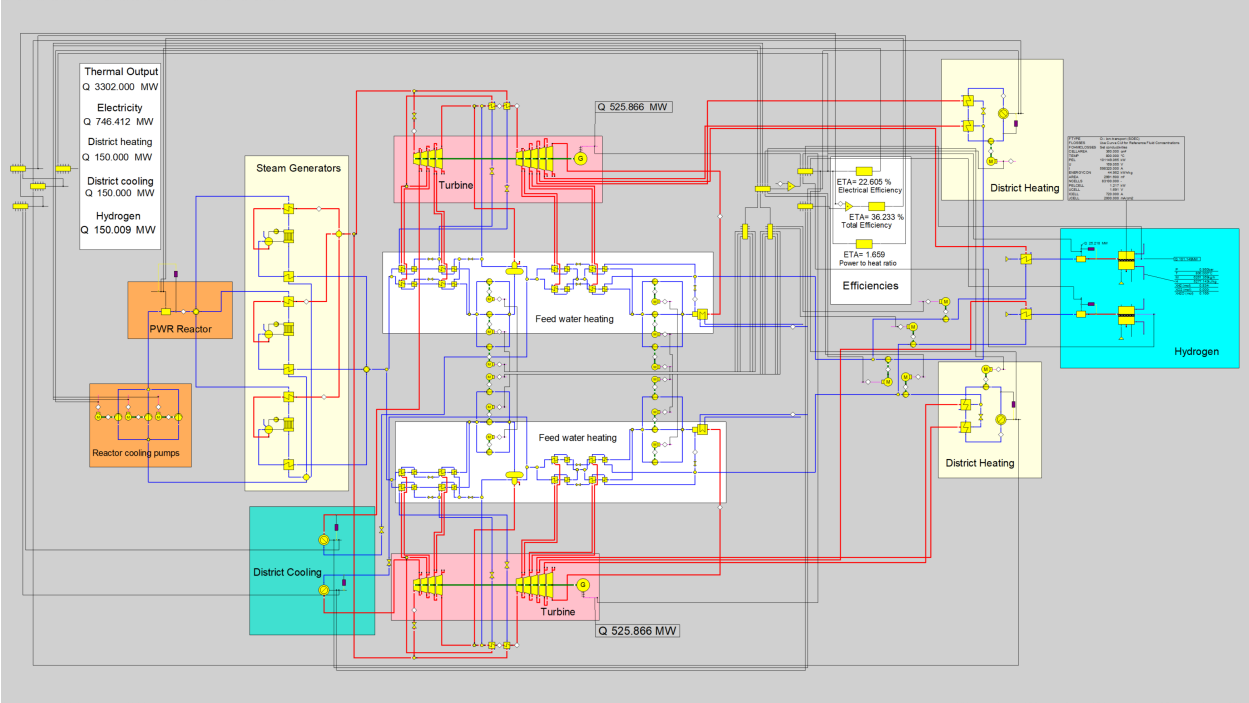


# Thermodynamic modelling and simulation in Nuclear Power

## The potential of energy utilities produced and delivered by Nuclear Power Plants

Master's thesis in Sustainable Energy Systems

ALEXANDER YOUNG

DEPARTMENT OF SPACE, EARTH AND ENVIRONMENT

CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Ebsilon Professional model of proposed multiple energy utility Nuclear Power Plant.

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# Abstract

As global energy demands rise and decarbonization efforts accelerate, nuclear power is poised to play a pivotal role as a reliable energy source. However, current nuclear power plants, are primarily optimized for electricity generation in a energy system which is seeing more and more suppliers, such as renewable alternatives through wind and solar power. This reduces the profitability and security of market share for nuclear power plant operators. Furthermore, most nuclear power plants experiences significant losses of low-grade thermal energy in the condenser resulting in low total plant efficiencies normally around 30-34%. This thesis explores how integrating additional energy utilities, specifically district heating, district cooling, and hydrogen production into nuclear power plants can increase total plant efficiency and improve economic viability.

Using *Ebsilon Professional* modelling software, a thermodynamic model of a three-loop pressurized water reactor validated based on Swedish Ringhals 3 and 4 reactors was developed. A reference case focused solely on electricity generation was established and compared against three energy utility integration scenarios: (1) District heating via low-pressure steam extraction, (2) District cooling through high-pressure steam-driven absorption chillers, and (3) hydrogen production using high-temperature electrolysis. Each case was evaluated in terms of plant performance and economic feasibility, considering efficiency impacts, investment costs and revenue potential.

The results of the modelling work show that while electrical efficiency decreases with steam extractions, total efficiency increases due to the utilization of steam to produce secondary energy utilities for both district heating and cooling cases. At 7.5 and 13% steam extractions the total efficiency increase of the nuclear power plant increases from 32.5 to 37%. For hydrogen the total plant performance decreases however as the steam extractions can't be utilized very effectively as there are no appropriate conditions present for electrolysis. Additionally the electricity demand for electrolysis exceeds the energy content of the produced hydrogen resulting in a decreased total efficiency. Through comparing these cases this thesis finds that district heating integration yields the largest increase of performance per percentage of steam extracted, and the largest revenue gains compared to district cooling and hydrogen implementation. To ensure positive revenue the required amount of district heating requires 1.42% of steam extracted which equals 40.39MW of utility demand. All energy utilities however showcase profitability if exceeding a certain demand.

Keywords: Pressurized Water Reactor, District Heating, District Cooling, Hydrogen

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Lastly I would like to thank Klas Andersson for reading this thesis and by doing so, further my skills as a researcher, the Department of Space, Earth and Environment at Chalmers and the department of Nuclear Technology at AFRY for making me feel welcome and inspired.

Alexander Young, Gothenburg, 2025

# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

| | |
|---|---|
| AC | Absorption Chiller |
| BWR | Boiling Water Reactor |
| CHP | Combined Heat and Power |
| CCHP | Combined Cooling Heat and Power |
| COP | Coefficient of Performance |
| DC | District cooling |
| DH | District Heating |
| FWH | Feed Water Heater |
| HRSG | Heat Recovery Steam Generator |
| HP | High Pressure |
| HX | Heat Exchanger |
| IEA | International Energy Agency |
| KSU | Kärnkraftsäkerhet och Utbildning |
| LP | Low Pressure |
| LWR | Light Water Reactor |
| NPP | Nuclear Power Plant |
| PEM | Proton Exchange Membrane |
| PWR | Pressurized Water Reactor |
| SMR | Small Modular Reactor |
| SOEC | Solid Oxide Electrolyser Cell |

# Contents

# List of Figures

# List of Tables

# 1

# Introduction

## 1.1 Background

The global energy demand continues to rise. In 2024, global energy consumption increased by 2.2%, a notable jump compared to the average annual increase of 1.3% between 2013 and 2023. Electricity demand in particular has grown the fastest, increasing by 4.3% [1]. This change in demand is also reflected in energy utilities such as heat and hydrogen, which will be the focus of this paper.

To meet this energy demand, burning fossil fuels is still very common. Coal still supplies just over a third of the global electricity generation even though it is the most carbon-intensive fossil fuel. Natural gas, which is the second largest electricity generation source, is representing more than 20% [2]. A figure illustrating the global electricity generation and its source is depicted in figure 1.1. Both the IEA and the World nuclear association reports that around 10% of the global electricity generation is done by Nuclear Power Plants (NPP's) [3] [2], while this value is significantly higher for the Swedish market, being around 30% according to the World Nuclear Association [4].

Heat, especially when co-generated with electricity in combined heat and power (CHP) plants, can be efficiently distributed to residential buildings through district heating (DH) networks. In addition to residential applications, industries across various sectors are also experiencing increased needs for both heating and cooling. Heating is a critical energy utility in industrial processes, used either from on-site generation or sourced from external suppliers. It plays an essential role in production processes across sectors ranging from chemical manufacturing to food preservation. One specific example of where heat and electricity is needed is for the production of hydrogen.

In Figures 1.1 and 1.2, the global generation of electricity and heat by source is presented. A notable observation is the stark difference in the share of nuclear energy, which accounts for approximately 10.3% of electricity generation but only 0.17% of heat production. This is due to most plants being built primarily for electricity generation. A number of other aspects also contribute to why heat generation is not very common for NPP's. Location can affect the effectives for distributing heat, as most NPP's are located far from major cities the losses for transporting heat can be substantial. Low temperature heat can also be met more cheaply by fossil fuels, biomass and waste. Lastly the public perception also influences the availability due to safety and contamination risks. These differences suggests that nuclear energy remains an underutilized source for heat generation, pointing to a potential opportunity for expansion in this sector.

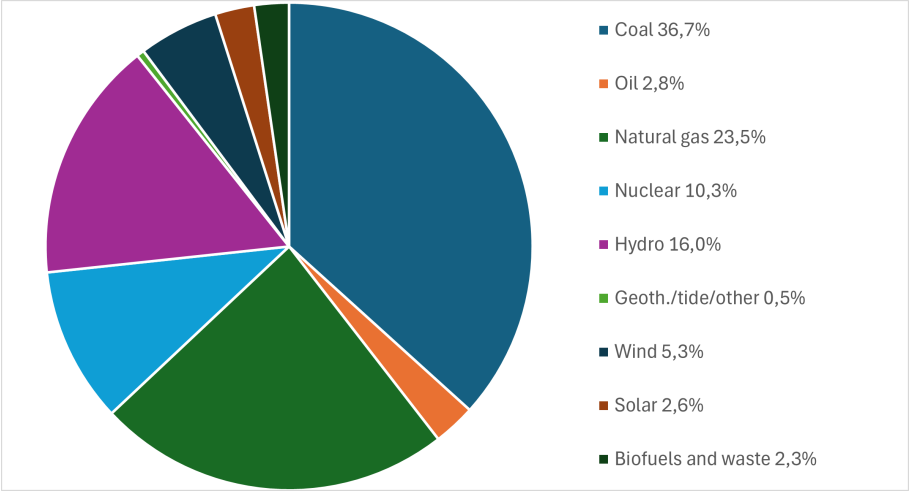


**Figure 1.1:** Electricity generation share by source globally, 2019, Electricity production, adapted from IEA 2025 [1].

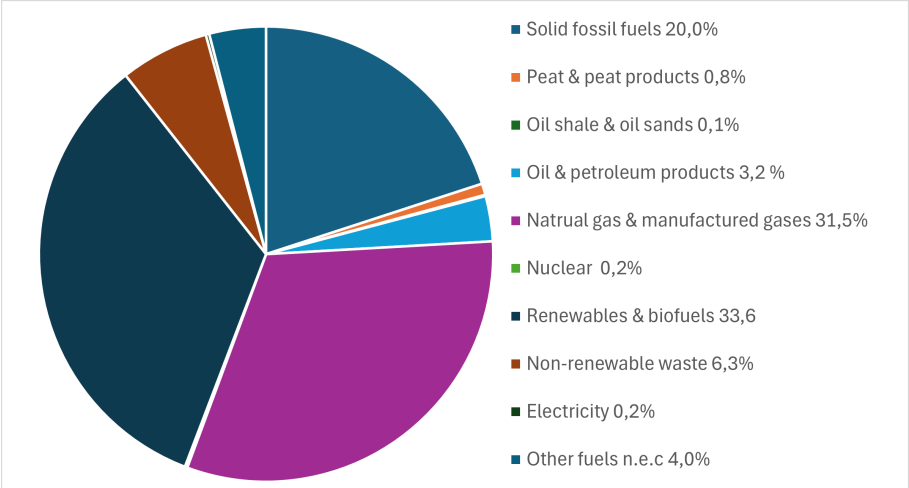


**Figure 1.2:** Derived heat production by source globally, Electricity and heat statistics, adapted from Eurostat 2022 [5].

Another important energy utility, hydrogen and especially renewable hydrogen is also seeing an increase in demand. The European commission put forth a strategy in 2022 which has the aim to produce 10 million tonnes of renewable hydrogen by 2030. Furthermore by 2050, renewable hydrogen is to cover around 10% of the EU's energy needs, significantly decarbonising energy intensive industrial processes and the transport sector [6].

In the context of generating electricity, nuclear energy plays a critical role. Unlike fossil fuels, nuclear power produces electricity with virtually no greenhouse gas emissions during operation. It offers a stable energy source, capable of supplying large amounts of base-load power regardless of weather conditions, a notable advantage over intermittent sources like wind and solar. Compared to other low carbon alternatives, such as biomass or hydropower, nuclear energy has a significantly higher energy density and a smaller land footprint, making it especially attractive in densely populated or geographically constrained regions.

Despite its advantages, the nuclear sector faces several challenges in meeting the current energy transition goals. One of the main hurdles is the limited utilization of the energy produced in nuclear plants. Today, nuclear reactors are primarily optimized for electricity generation, and a considerable portion of the thermal energy is wasted in the condenser as low-grade exhaust steam. Current nuclear plants typically operate with thermal efficiencies of around 30–34%, meaning nearly two thirds of the thermal energy generated is not converted into useful electricity[3]. By harnessing this residual heat for additional energy utilities such as district heating, district cooling or hydrogen production, the total efficiency of the NPP's could be significantly improved. Note that different energy utilities require heat at different temperatures and pressures to operate their different components. The absorption chillers used for producing district cooling require significantly higher temperature steam than that of the heat exchangers used for district heating. As the requirements and operating conditions differ between the different utilizations careful consideration needs to be made to accompany for this. Furthermore, certain hydrogen production technologies requires steam at temperatures above the available steam produced by a NPP and additional components need to be introduced.

As renewable energy sources like wind and solar continue to expand, the electricity market is affected in numerous ways. Reduced electricity prices due to renewables being lower in the merit order, especially at moments of high penetration of wind and solar such as windy and sunny days is one such effect. As these options become more relevant and sufficient for the energy demands the capacity factor for other producers such as nuclear decreases. The overall share of demand is also reduced for electricity focused generation plants. This shift could reduce the marginal profitability of electricity-focused generation such as nuclear. However, by transitioning to a multi-utility production model, nuclear power can maintain—and potentially

grow—its market relevance. Furthermore, many current sources of industrial and residential heat rely on fossil-based or solid fuels, such as coal or biomass. These sources could be gradually replaced or relocated to other applications, with nuclear energy filling the gap through stable, carbon-neutral heat delivery. This shift would reduce emissions and offer greater long-term sustainability and price stability. As renewables sources are also intermittent sources the need for grid stability and storage of energy is also increased. Storing energy in the form of hydrogen is one potential solution for providing flexible energy storage.

A multi-utility production schematic design of a NPP is shown in figure 1.3

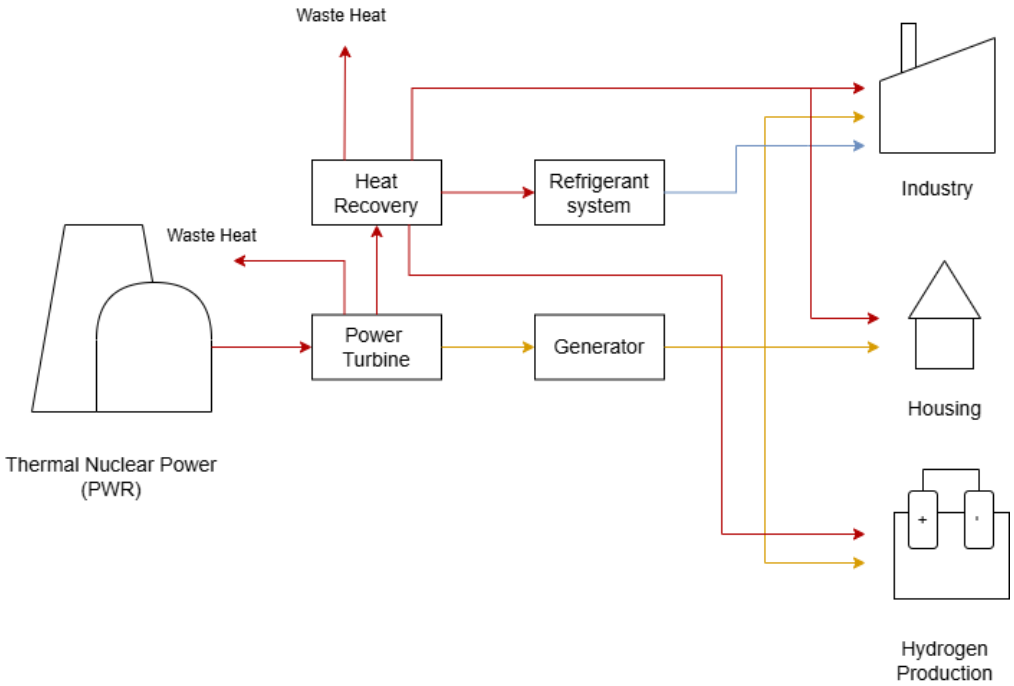


**Figure 1.3:** Conceptual Design of PWR and trigeneration system with hydrogen production, designated streams as heat(red), cooling(blue), power(yellow), (adapted and modified from [7])

## 1.2 Aim and Scope

The aim of this thesis is to investigate how the integration of additional energy utilities into nuclear power plants, specifically district heating, district cooling, and hydrogen production, can improve overall plant efficiency, and economic viability. By modelling and simulating these integrations using a validated thermodynamic model of a PWR, the thesis aims to evaluate the technical and financial impacts of shifting nuclear plants from electricity-only producers to co- or trigeneration systems.

The focus of this thesis will be on the PWR type and therefore leaves other configurations for future work. As all performance and economic assessments are based on the reference model, this thesis aims to provide a flexible model that can be configured to represent various PWR setups and should be validated against one such configuration before continuing with the new implementations. The reference model should be representative of a general large scale NPP and therefore SMR's are not evaluated in this thesis.

Through economic assessment, the new components required for implementing these energy utilities are evaluated based on their respective investment costs. The economical calculations should also account for revenue gains and losses which accompany these new energy utilities supplied by the NPP. As the revenue from distributing these different energy utilities could be dependant on the location of the NPP the economical assessments should also account for seasonal demand changes as well as price. Moreover, all performance comparisons are made relative to the validated reference model, assuming constant reactor thermal output. Economic calculations focus on investment and revenue changes based on demand of the added energy utility and do not include full lifecycle cost modelling for new investments.

# 2

# Theory

## 2.1 Nuclear Power

The overlying workings of a NPP is to utilize the heat that is generated through fission in the core of the reactor to heat the feed water in a boiler to produce steam. Uranium nuclei in the fuel are bombarded by neutrons which causes them to split, releasing energy in the form of heat, as well as more neutrons. Some of these released neutrons then cause further fissions, thereby setting up a chain reaction. The fuel consists of enriched uranium dioxide as natural uranium only contains 0.7% of the fissile U-235 isotope. The remaining 99.3% is mostly the U-238 isotope. By contrast to the U-235 isotope, the binding energy released by U-238 absorbing a thermal neutron is less than the critical energy, so the neutron must possess additional energy for fission to be possible. A self sustaining chain reaction is therefore not achievable if the U-235 fraction is not increased. In this enrichment process the fraction of U-235 is increased from 0,7 to 3-5 % [8] [9].

The two most common reactor types are pressurized water reactors (PWRs) and boiling water reactors (BWRs). Both these reactor types are collectively known as light water reactors (LWRs), the light water ($H_2O$) coolant is also the moderator. The chain reaction is controlled by the use of control rods, which are inserted into the reactor core either to slow or stop the reaction by absorbing neutrons. A PWR generates steam indirectly as heat is transferred from the primary reactor coolant, which is kept liquid at high pressure, into a secondary circuit where steam is produced for the turbine. A BWR produces steam directly by boiling the water coolant. [10] The heat generated in the reactor fuel is transferred to the reactor water through conduction and convection. The focus off this paper will be the PWR.

The PWR model consists of two separated circuits: the reactor side of the nuclear power plant, which provides heat to the system, and the other consists of the steam cycle, which utilizes that heat to generate steam and subsequently electricity. To

simplify the explanation of the model and to understand the dependencies in the system the nuclear power plant is divided into four subsystems: the reactor; the steam generators; turbines combined with generators; condenser combined with feed water pre heaters. To ensure increased redundancy and safety NPP's operate with a high amount of duplicates in regards to both streams and components. These are distributed both in a parallel and series configuration. The model incorporates three loops for heat distribution from the reactor, three steam generators, two turbine branches each consisting of of a high pressure (HP) turbine and a low pressure (LP) turbine and a set of parallel series of feed water heaters. If one loop fails or is in need of maintenance (e.g., due to a pump malfunction or pipe rupture), the remaining loops can continue to cool the reactor, reducing the risk of core damage as well as continuous production of steam and power. In a NPP safety of operation is of the utmost importance.

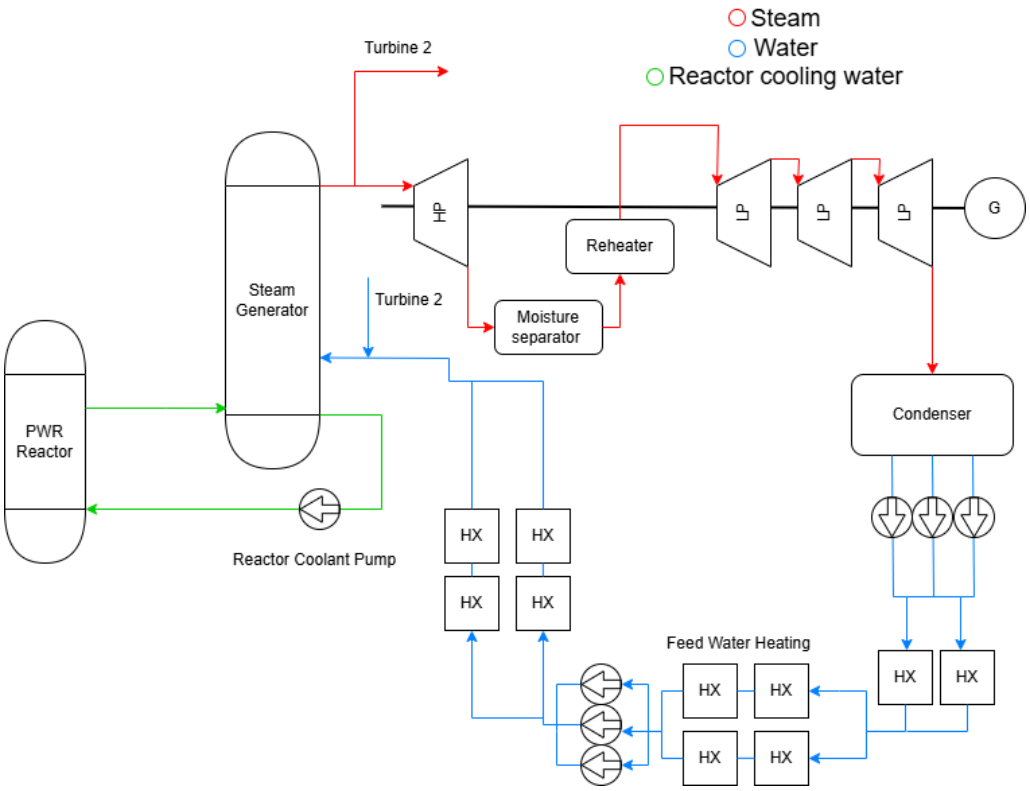


**Figure 2.1:** Schematic of proposed PWR configuration adapted from [11]

The primary safety measure are at all times to ensure that the cooling water around the reactor never is allowed to boil or stop circulating. The continuous removal of water and with it, heat from the reactor, ensures that the water temperature remains below its boiling point, preventing it from vaporizing and expanding as liquid and gaseous water have drastically different specific volumes. In the upper part of the core, where the void fraction is highest, there is a risk of a condition called dryout. This can occur when the water film around the fuel rods evaporates. A gas such as steam conducts heat very poorly, and therefore the heat transfer between the fuel rod and the coolant decreases drastically, meaning that most of the heat energy remains in the fuel. This would cause the temperature of the fuel rods to rise rapidly,

which can lead to fuel damage or meltdown if the condition persists.

## 2.2 Rankine cycle

There are a couple of fundamental differences between conventional fossil fuelled plants and NPP's when it comes to operating conditions for the steam cycle, such as steam pressure and temperature. In a conventional power plant, heat is typically generated by the combustion of fossil fuels such as coal, oil, or natural gas. The combustion process can reach very high temperatures, allowing for high steam pressures (20–30 MPa) and superheated steam temperatures up to 540–600 °C. These high-temperature and high-pressure conditions result in greater thermodynamic efficiency as compared to NPP's. Additionally, some conventional plants like gas turbine combined cycles use supplementary firing, such as natural gas burners in the boiler or heat recovery steam generator (HRSG), to further superheat the steam before it enters the HP turbine [12]. This increases the energy content of the steam, improving the expansion process in the turbine and boosting efficiency.

Steam generators (SG's) are commonly used in pressurized water reactors (PWRs) and consist of a bundle of tubes where the primary coolant flows inside, while the secondary water surrounds the tubes and boils into steam without mixing with the radioactive primary loop. Normal lives steam conditions of the steam produced vary depending on reactor type. For a PWR live steam conditions range usually from 275-285 °C and 60-70 bar [13]. The steam is then led to the turbines which consist of both a HP turbine and three LP turbines. Following the first law of thermodynamics the turbine work output can be calculated by the mass flow of the stream and the enthalpy loss over the turbine according to the following equation

$$\dot{W}_{tubrine} = \dot{m}(h_{inlet} - h_{outlet}) \tag{2.1}$$

The turbines however are not perfectly efficient and the isentropic efficiency must be taken into account according to:

$$\eta_{turbine} = \frac{h_{inlet} - h_{outlet}}{h_{inlet} - h_{outlet,s}} \tag{2.2}$$

The mechanical power from the turbines is transferred to a generator which induces electrical power

$$P_{electrical} = \eta_{generator} \cdot \dot{W}_{turbine} \tag{2.3}$$

While steam turbines are highly efficient machines for converting thermal energy into mechanical and ultimately electrical energy, they face several design and operational limitations, particularly in the LP stages. As steam expands through the turbine, especially in the LP stages, its specific volume increases significantly. To accommodate the resulting high volumetric flow rate, LP turbine blades must be extremely long, resulting in a large turbine radius. This large radius leads to a much greater rotating mass, which imposes significant mechanical stress on the rotor, bearings, and shaft. The high inertia of the rotating mass also reduces the turbine's ability to respond quickly to load changes, making it less flexible under dynamic operating conditions which is one reason for nuclear to operate as base load.

Another major challenge in LP turbines is the presence of moisture. As the steam expands and cools, it often becomes partially condensed, resulting in wet steam entering the final stages. The water droplets within the steam can cause severe erosion on the turbine blades due to droplet impingement. This problem is especially relevant for NPP's as the live steam conditions entails that the expansion over the turbines quickly lead to wet steam conditions. To mitigate this, moisture separators and re heaters are installed in between the HP turbine and the LP turbine to keep the moisture content at acceptable levels. By reheating the steam before it enters the LP turbine the efficiency of the plant can also be increased as the temperature difference over the turbine is higher resulting in a bigger difference in enthalpy.

In a condensing power plant, condensers play a vital role in completing the steam cycle by converting the exhaust steam from the LP turbines back into liquid water, referred to as condensate. This condensation is essential to allow a fixed amount of water to be pumped back into the steam generator or heat exchanger, thus maintaining a continuous and efficient steam cycle. To ensure safety of operation there are two separate condensers, one for each turbine shaft. This configuration allows for independent control and operation of each turbine line and simplifies maintenance and load balancing across the system. In a NPP the condenser operates below ambient pressure to improve efficiency and condensation. The low pressure allows steam to expand more in the turbine, generating more electricity. It also lowers the boiling point, making it easier to condense the steam back into water using cooling water. Inside the condenser, thousands of metal tubes carry the cooling water sourced from either a nearby water body or a cooling tower system. As the low-pressure steam contacts the cooler surfaces of these tubes, it condenses into water. This condensate collects at the bottom of the condenser and is then pumped back into the feedwater system. The cooling water that absorbs the steam's heat must itself be cooled before being recirculated. If the plant uses a natural water source, the heated cooling water is returned to the environment at a slightly elevated temperature. However, envi-

ronmental regulations typically limit the allowable temperature increase to around 10–15°C to protect aquatic ecosystems. If the plant uses a cooling tower, the warm cooling water from the condenser is pumped to the top of the tower and distributed over a large surface area. Air flows through the tower either naturally or with the help of fans—causing some of the water to evaporate. This utilizes the relationship between wet and dry bulb temperatures. This evaporation removes heat from the remaining water through the process of convective and evaporative cooling. The cooled water then collects at the base of the tower and is pumped back to the condenser.

The condensate is returned to the steam generator through a series of heat exchangers which gradually increase the temperature of the feed water. This series of temperature increases reduces the amount of fuel needed to supply the necessary heat for evaporation. In a NPP both closed and open heat exchangers are utilized where closed HXs does not mix the fluids and where the heat transfer is done through a physical wall. An open heat exchanger however sprays the steam into the liquid feed water heating the mixture and dissolving any build up of gases.

Through out the system pumps and throttles are utilized to ensure that the pressure of different streams are correct. The pumps will utilize electricity through a connected motor to drive the pump work. This decreases efficiency as the total amount of electricity that is available for delivery is reduced to compensate for pressure losses through out the system [14].

$$w_{pump} = h_{inlet} - h_{outlet} \tag{2.4}$$

$$P_{pump} = \dot{m} \cdot w_{pump} \tag{2.5}$$

To evaluate the system the electrical power output produced by the generators and the thermal ouptut from the reactor describes the working conditions of the plant. These can also be related to each other to evaluate the efficiency of the plant in the following terms:

$$\eta_{thermal} = \frac{\dot{W}}{Q_{in}} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{Q_{in}} \tag{2.6}$$

$$\eta_{electrical} = \frac{P_{tubrine} - P_{pump}}{Q_{in}} \tag{2.7}$$

$$\eta_{total} = \frac{P_{net} + Q_{out}}{Q_{in}} \tag{2.8}$$

$$\alpha = \frac{P_{net}}{Q_{useful}} \tag{2.9}$$

In a NPP however, the materials and safety requirements in nuclear systems impose strict limitations on temperature and pressure. As a result, steam conditions are much lower, typically around 6–7 MPa and 270–300 °C, and the steam is often saturated or only slightly superheated. This leads to lower thermal efficiency, usually in the range of 30–35%, compared to 40–45% or more for modern fossil-fuel plants [11].

## 2.3 District heating and cogeneration

To increase the total efficiency ($\eta_{total}$) of the NPP other energy utilities could be implemented. By extracting steam before it reaches the condenser, high-quality steam can be utilized in other processes, thereby increasing the overall efficiency of the plant. To achieve a higher conversion of the thermal output from the reactor a DH systems heating needs could be supplied by the NPP resulting in less heat being lost as waste heat as it arrives at the condenser. To supply the heating required by the DH system a series of turbine extractions will be made from the LP turbine which will then supply hot steam at sufficient conditions. These steam extractions will flow through a heat exchanger which will transfer the heat to the DH loop. As the DH producing steam cycle requires water to be heated from 40 to 100 °C according to table 2.1, appropriate extractions between 0.7 and 1 bar can be made as the saturation temperature at these pressures are sufficient to heat the DH water.

DH systems can be operated in two different configurations; back pressure and extraction variants. In this project only the extraction version will be evaluated as it is the only version compatible with NPP's. Extraction systems utilize the steam flowing through the turbines upstream of the condenser as this yields higher temperatures for the extraction. This is important as the steam being extracted needs to have temperature conditions above the return temperature of the DH water as well as the water being supplied to the DH system for the heat transfer of the heat exchanger to be achieved. In a gas or waste driven combined heat and power plant (CHP) the temperature of the steam arriving at the condenser are at much

higher temperatures, making the use of back pressure condensers for heat exchanging the DH water attractive. This also differs depending on where it is operational as Sweden implements this strategy because of high DH demands. Because of the cold winters the Scandinavian market requests more DH supply compared to other places such as continental Europe. Therefore, the operating conditions are dependant on the type of energy utility demanded. In the back pressure condenser the excess heat left in the steam could be cooled as well as heat the cooling medium of the condenser [15]. In conventional CHPs the cooling medium could be replaced by the district heating system which then incorporates both heating and cooling of the respective streams. However the temperature of the NPP's inlet to the condenser is around 29°C, which is not sufficiently high to heat the DH water [11]. In table 2.1 normal operating conditions of a DH system located in Gothenburg, Sweden are summarized. This demonstrates that the temperatures at the condenser in a NPP are too low to heat the district heating water, making steam extraction at higher temperatures the only viable option.

**Table 2.1:** Operating temperatures for DH based on values from Göteborg Energi [16]

| **Stream** | **Temperature °C** |
|---|---|
| Outgoing DH water | 100 °C |
| Returning DH water | 40 °C |

## 2.4 District cooling and trigeneration

There are a number of different types of industrial chillers which utilizes different types of medium to achieve the cooling effect. One group of these are water and air cooled chiller which rejects the heat from a stream with the help of water or air. The transfer of heat is driven by convection and conduction by having either fans, coils or cooling towers to cool the stream. These applications are common when cooling is needed on-site and there is no natural body of water apparent for cooling purposes. The other category is based on the refrigeration cycle and can either utilize electricity to drive compressors for cooling or use waste heat from power plants or process industries to drive the cooling [17]. It is the latter which will be modelled and investigated in this paper. The Coefficient of Performance (COP) of an absorption chiller (AC) is a measure of its efficiency and is defined as the ratio of useful cooling output to the thermal energy input required to drive the process. The thermal COP usually ranges between 0.6 and 1.2 for an $H_2O - LiBr$ absorption chiller which is used in this project [18], and is defined in equation 2.10.

$$COP = \frac{Q_{\text{useful}}}{Q_{\text{input}}} \tag{2.10}$$

An absorption chiller is a cooling system powered by heat, the difference compared to a vapour compression system is that the mechanical compressor found in the vapour-

compression systems is replaced by a combination of an absorber, a solution pump, and a generator. This setup allows absorption chillers to utilize waste heat efficiently, making them a valuable alternative when cooling is needed in settings with excess thermal energy such as a NPP. A schematic of the workings and components of this type of absorption chiller is shown in figure 2.2 [19] and described below. The system operates using two working fluids: a refrigerant and an absorbent. The refrigerant is added to the absorbent, enabling the transfer of heat. Inside the chiller, three primary flow paths are maintained: the strong solution, the weak solution, and the refrigerant. In the proposed system, water acts as the refrigerant, while lithium bromide serves as the absorbent, this is the most common type of absorption chiller. The cycle starts when the strong $H_2O - LiBr$ solution, after absorbing refrigerant vapour in the absorber, flows through the solution heat exchanger. Here, it gains heat from the weak solution, aiding the separation of water from lithium bromide in the generator. The separated water vapour proceeds to the condenser, while the lithium bromide-rich solution returns to the absorber. In the condenser, the water vapour releases heat and condenses into a saturated or sub-cooled liquid. This liquid is then expanded through a valve, reducing its pressure to match that of the evaporator, where it absorbs heat from an external chilled water loop. As a result, the refrigerant evaporates into a saturated or superheated vapour, producing the cooling effect. The resulting vapour travels to the absorber, where it mixes with the weak solution returning from the generator. As this mixture releases heat to the surroundings, a strong solution is formed again. This strong solution is pumped through the heat exchanger and back into the generator, completing the refrigeration cycle [20]. Depending on the type of chiller it can either operate as single stage or two stage, which indicates the number of generators. In these version high temperature steam at around 200 °C is needed. Which then leads to steam extractions at at least 16 bar.

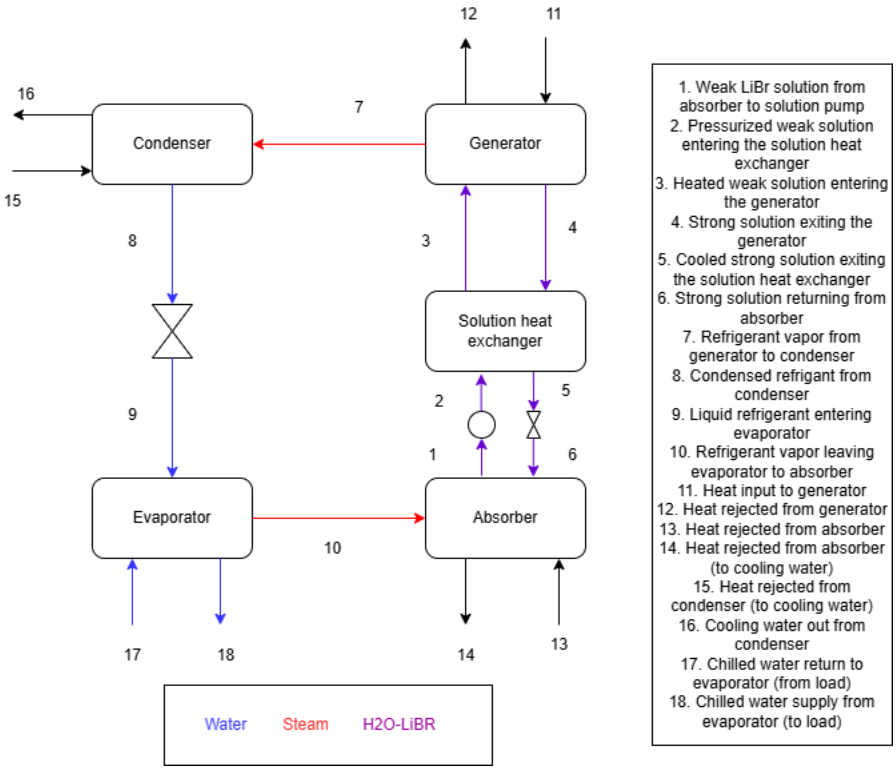


**Figure 2.2:** Typical workings of $H_2O - LiBr$ absorption chiller, adapted from [19]

## 2.5 Hydrogen production

Hydrogen can be produced through various methods. These can differ based on the process used such as steam methane reforming or through electrolysis. The electricity source used to achieve the hydrogen production, be it from renewables, fossil fuels or nuclear can also differ and therefore there are different groupings of hydrogen production. These are usually named after a colour describing from which source the electricity utilized is generated. By using fossil fuelled sources for the electricity the colour accompanied is grey, resulting in grey hydrogen [6].

When producing hydrogen from a NPP the colour associated is pink. This hydrogen is produced by utilizing the electricity produced on site to drive the heating and splitting of steam to produce hydrogen. There are three different main electrolyser types, Alkaline, Proton Exchange Membrane (PEM) and Solid Oxide Electrolyser Cell (SOEC). All of these types of electrolyser have the same overlying reaction of:

$$2H_2O \xrightarrow{electrolysis} 2H_2 + O_2 \tag{2.11}$$

However the mechanism, electrolyte, and operating conditions differ significantly.

The focus in this thesis and modelling work will be on the SOEC as this outperforms the other two in terms of efficiency due to operating at much higher temperatures. By operating at higher temperatures, around 750-850 °C, the SOEC utilizes high temperature electrolysis. As higher temperature steam contains higher amounts of energy as the enthalpy of the steam (total energy content per unit mass) lowers the needed electricity to split molecules and opens up for new, potentially better electrolytes like molten salts or hydroxides. As there are no extractions available to heat the steam to such high temperatures an alternative heating method such as an electric boiler or a oil or gas burner is needed in the case of NPP's. However a steam extraction can be made to preheat the steam to reduce electricity needed in the boiler. An extraction can be made which supplies steam that could pre heat the electrolyser water from ambient conditions to saturation temperature. The water which is used in the electrolyser can be sourced from a natural water source such as the ocean. This alternative is quite efficient as most NPP's are located by a water source. The operating pressure of the electrolyser ranges usually from 1-5 bar [6], making steam extractions at the similar pressure ranges appropriate. In fact, at 2500 °C, electrical input is unnecessary because water breaks down to hydrogen and oxygen through thermolysis. A SOEC operates as a solid oxide fuel cell but in reverse, using a ceramic electrolyte to split water into hydrogen and oxygen. This high-temperature electrolysis process is highly efficient and produces pure hydrogen, a clean and storable energy utility that offers an alternative to batteries. Among current technologies, electrolysis of water stands out as the most promising method for renewable hydrogen production due to its high efficiency and lower energy demands compared to thermochemical and photocatalytic methods. The hydrogen produced can then be stored in several different ways, such as compressed hydrogen gas, liquid hydrogen or in an ammonia suspension depending on application, scale and infrastructure [21].

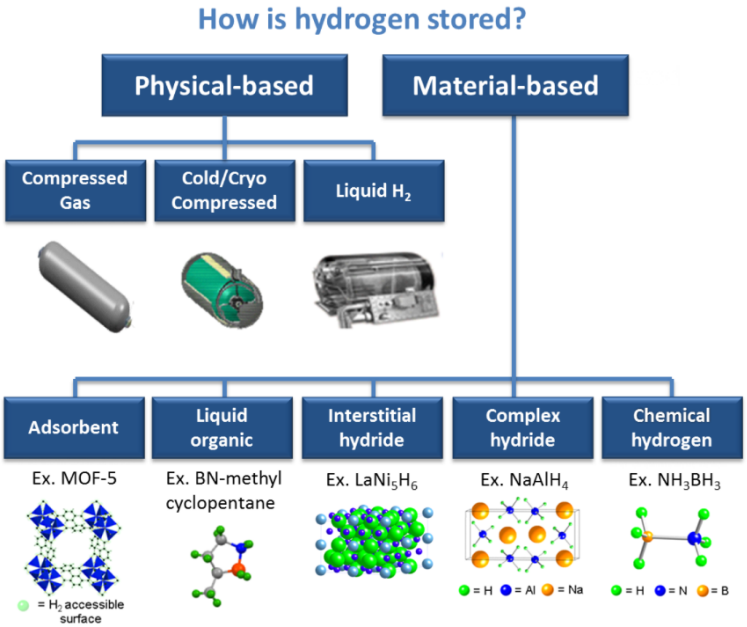


**Figure 2.3:** Storage methods for hydrogen, gathered from [21]

# 3

# Methods

This chapter focuses on describing the different areas covered in the thesis work. The chapter will be divided into sections including the description of the modelling and simulation work done in *Ebsilon Professional*, the validation of the reference model against published literature, performance analysis and a techno-economic evaluation of the examined energy utilities. By constructing a reference model of a currently operating NPP and validating the operational conditions according to published literature the thermal output of the PWR is determined. By keeping the thermal output constant new additional energy utilities are implemented to the reference model. These are then evaluated on how additional utility demands affect the performance and economical incentive of the suggested implementation. In the following sections general variables are used in equations and calculations, a full list of the values and variables used in both technical and economic calculations are presented in Appendix B and C.

## 3.1 Process modelling

This section describes the modelling work done in Ebsilon professional [22]. Ebsilon Professional is a simulation and modelling software for thermodynamic cycle processes. The modelling work is the foundation for the analysis described in later sections which evaluate the NPP in regards to its performance, efficiency and costs. The following sections will introduce the base model of a three-loop PWR, presented in section 3.1.1 as well as the three different cases of new installations to the plant in sections 3.1.2 - 3.1.4. These include: two different cases of cogeneration which supplies electricity and either district heating or cooling; trigeneration which supplies electricity, heat and cooling and finally hydrogen production as a separate energy utility.

### 3.1.1 Reference case

Mayor components are highlighted in figure 3.1 and are as follows: PWR reactor (orange), Steam generators (yellow), Turbines (pink), Condenser and FWH (white). In this model production outputs and efficiencies are also highlighted in white. Inspiration for system design came from KSU [11] and proposed designs in the following papers [23] and [24].

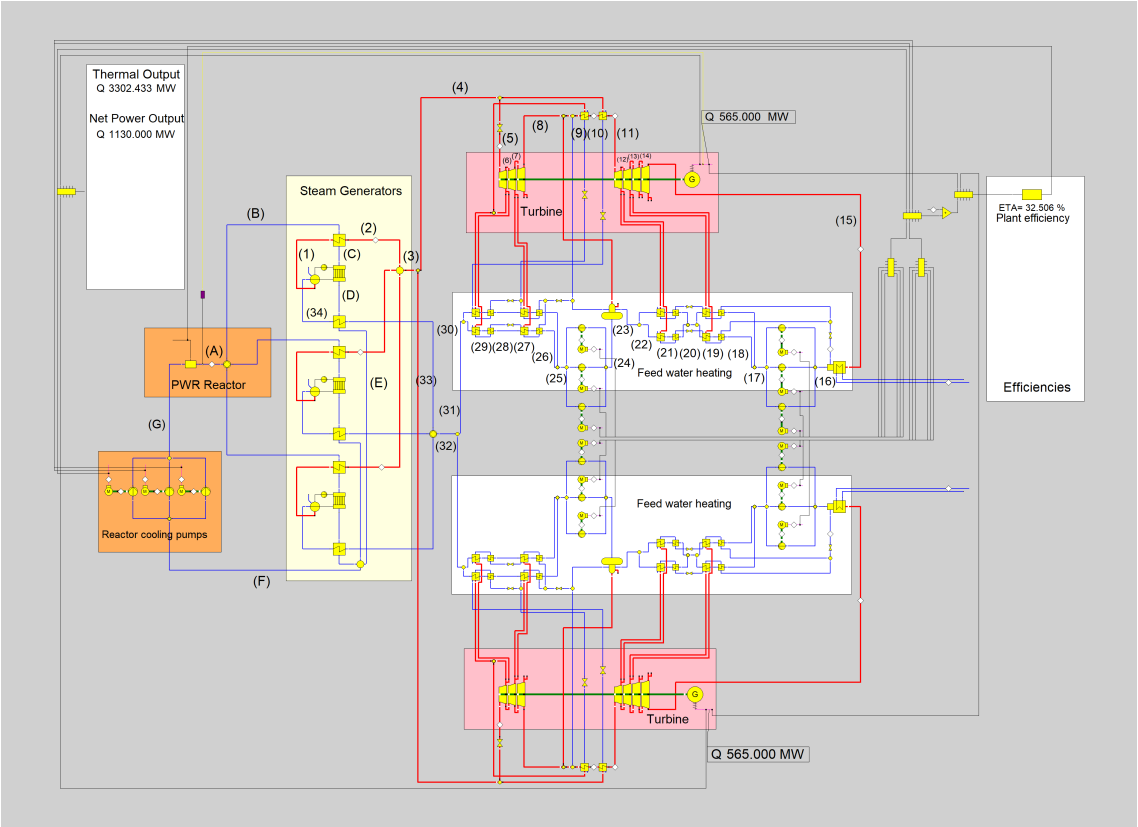


**Figure 3.1:** Base operational model for NPP, PWR configuration

The reactor is not the focus in this thesis and is simplified and modelled using a heat injector, which increases the temperature of the reactor cooling water returning from the steam generators from 286 to 323 °C. The reactor subsystem delivers heat to the three steam generators equally. The plant is controlled to generate a targeted electricity production, by adjusting the reactor heat input. This controller ensures that the mass flow of the hot water is sufficient to drive the evaporation in the steam generators, as the expansion of this steam converts the heat to mechanical work. The mechanical work is then converted into electricity through the generator. The reactor cycle also includes a configuration of three parallel reactor cooling pumps which ensures that a sufficient amount of cooling water is supplied to the reactor. These reactor cooling pumps also compensates for the pressure loss over the steam generators.

Intertwined with the reactor circuit are the three steam generators. The steam generator includes economizer, evaporator and superheater to ensure that the feedwater returning from the condenser and the steam leaving the steam generator are at the correct temperatures. The live steam leaving the steam generator is at 63 bar and 279 °C. The superheaters in contrast increases the saturated steams temperature which is produced from the evaporator, superheating the steam. For the reference model these superheaters are not active and do not superheat the steam above saturation temperature. This is done in accordance to the operational conditions of the live steam produced by the validation data of Ringhals 3 and 4 [25], [26]. They were instead added to the model to be able to either extract steam at higher temperatures or evaluate the effects on efficiency by increasing the temperature of steam above saturation temperatures before entering the HP turbine.

The steam produced in the three generators is firstly combined through a mixer to then be split into two separated steam headers, each having its own turbine series comprised of a HP turbine and a LP turbine. For modelling purposes each turbine extraction is represented by its own turbine component but with a distinction between HP and LP. By expanding steam through the turbine work is generated, but as the enthalpy of the steam decreases the moisture content increases. Once the moisture content reaches the accepted threshold of 15% between the HP and LP turbine, a moisture separator drains a fraction of the liquid water from the steam so that the liquid content is below 7%, where as re-heaters dries the steam to saturation once again. The moisture separator reduces the amount of heat needed in the re-heaters to dry out the steam and bring it to saturation temperature. This reduces the heat needed in the re-heaters increasing heat available through the expansion, increasing efficiency. The re-heaters utilize heat both from the live steam and from the HP turbine extraction to superheat the steam to 260 °C at 4.6 bar before it enters the LP turbine. This is done in two steps, because if the steam exiting the HP turbine is still wet, heating it directly to a high superheated temperature could cause excessive thermal stresses on the heat exchanger tubes. By first bringing it to the saturation temperature, all remaining moisture evaporates before further superheating. This prevents erosion and improves heat transfer efficiency.

The last part of the system are the condenser and FWH. In theory an unlimited number of FWH's would be ideal as this gives a steady increase of temperature from the condenser to the steam generators. However, a realistic approach based on KSU material [11] on how NPP operate in Sweden today is to incorporate ten, both open and closed FWH's. These all utilize the steam extractions from the turbines to preheat the water returning from the condenser before it again enters the steam generators. The FWH's in this model are comprised of two components, a FWH and an aftercooler. The feed water is lastly combined from both branches and then split to flow equally through the steam generators again, completing the cycle.

To evaluate the performance of the reference model the electrical efficiency is used based on the thermal output of the reactor and the electrical output of the generator. To take into account the amount of electrical output available for distribution, in-house consumption needs to be removed from the total electrical generation. According to [26] an 1130MW NPP consumes 5% of total generation as own consumption. By adding a calculator component to the model this in-house consumption can be taken into account and therefore reducing the electrical efficiency. In addition, to ensure that the total efficiency of the NPP is closely performing according to the validation data an isentropic efficiency calibration is made to the turbines. Resulting in an isentropic efficiency of 88 and 85% for the LP and HP turbine respectively.

### 3.1.2 Case 1 - District heating

As the outlet and inlet temperature of the DH water from the heat exchangers are known and presented in table 2.1 as 100 and 40 °C respectively, appropriate extraction temperatures and subsequently pressures could be determined. These extractions were made at 1.0 and 0.7 bar respectively resulting in steam extraction temperatures at 114.75 °C and 89.93 °C. The choice to install two heat exchangers in series was made to achieve a higher efficiency. By doing this the difference in temperature between hot and cold side can be decreased resulting in decreased exergy losses. This also results in the steam being able to expand further to lower pressures generating more electricity. The condensate from these HXs is returned to the condenser. The DH heat demand controls the mass flow of the DH water which then determines the mass flow of steam required through the extractions. The minimum temperature difference, $\Delta T_{min}$, was chosen as 2 Kelvin for all DH heat exchangers and determines the minimum allowable temperature approach between the hot and cold streams. A smaller $\Delta T_{min}$ allows for greater energy recovery but requires a larger heat transfer area, leading to increased capital costs. This was chosen so that the DH implementation operates more efficiently as the temperature of the steam extractions are not very high and heat utilization is of most importance. The addition of DH components are highlighted in yellow. To evaluate the performance and the profitability of the newly installed DH components simulations of different DH demands were made ranging from 10-200MW. These DH demands utilizes around 1-8% of the steam available for expansion, reducing the available amount for electricity generation by the same value.

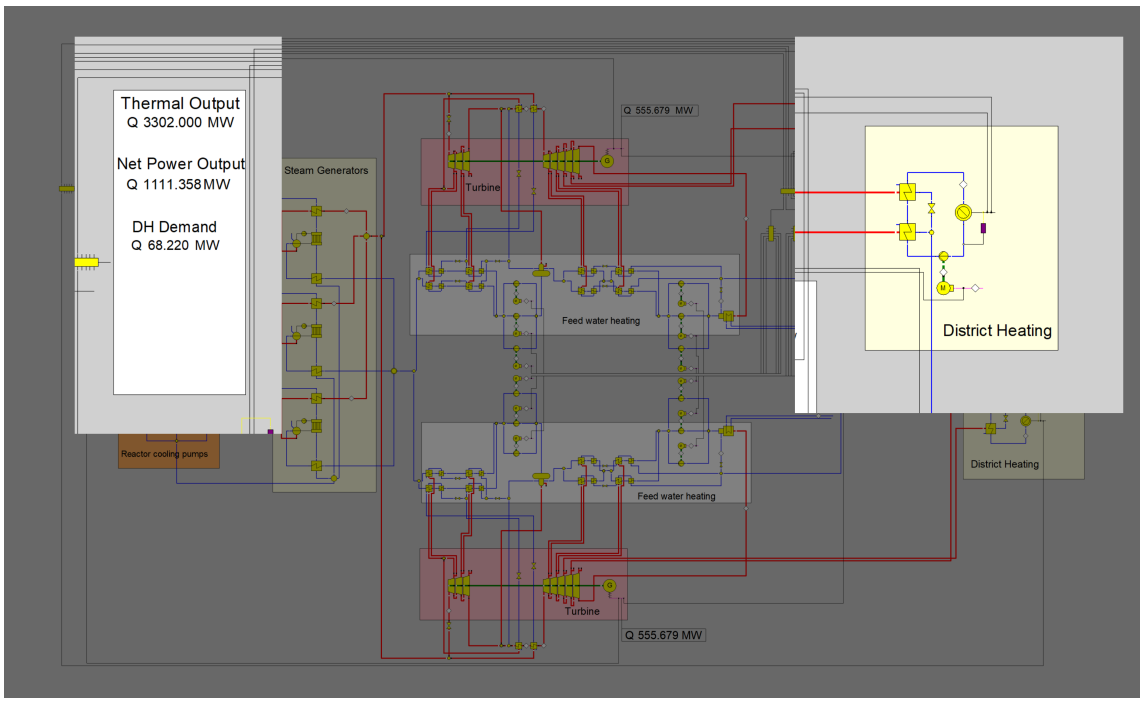


**Figure 3.2:** Implementation of a district heating system to the NPP

### 3.1.3 Case 2 - District cooling

In the case of district cooling the required steam that drives the absorption chillers need to be significantly higher than that of the DH extractions. The absorption chillers utilize heat at around 240 °C and therefore an extraction at 35 bar was made to supply the required steam. In real applications the absorption chillers consists of multiple components such as condenser, generator, heat exchanger, evaporator and absorber, these are replaced in the modelling with heat consumers. The model also include the condensate which is returned to the feed water heating system as it would in a real application. The addition of the DC components and demands are shown in figure 3.3 and are highlighted in turquoise.

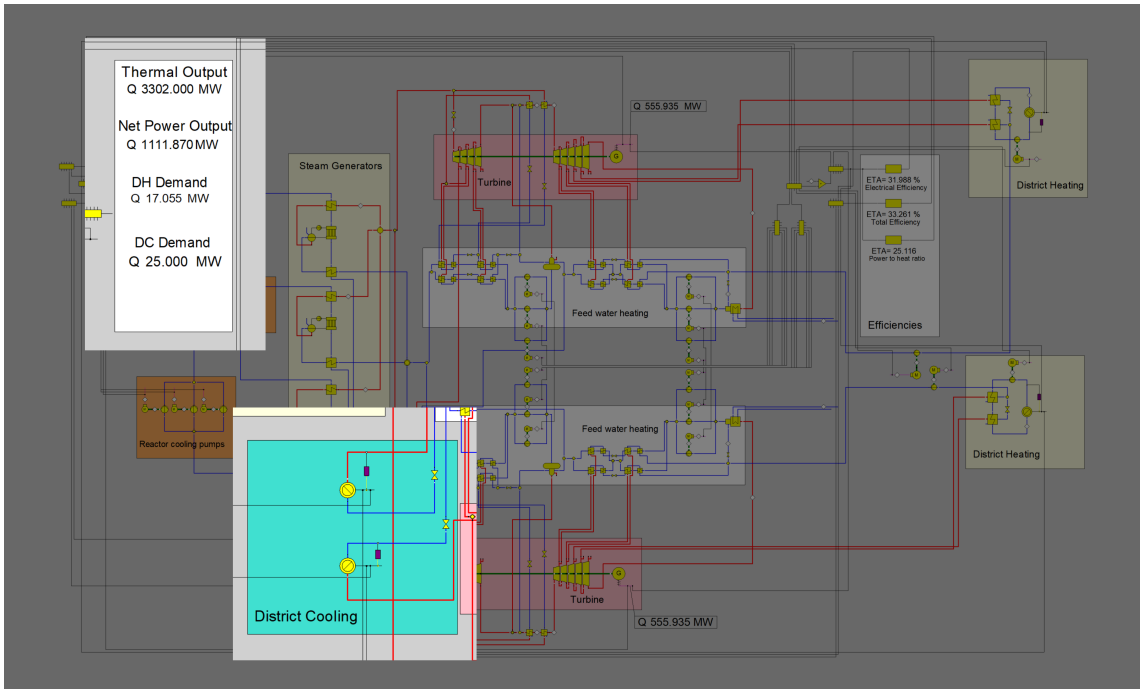


**Figure 3.3:** Implementation of a district cooling system to the NPP

To evaluate the performance and profitability of the new implementation of DC, simulations were made where the DC demand was ranged from 20 to 500MW with increments of 10 MW. This was the equivalent of extracting up to 15% of the available steam to drive the absorption chillers. These simulations generated values for electrical, total and thermal efficiency as well as the sizing and investment costs of the absorption chillers.

### 3.1.4 Case 3 - Hydrogen production

To accomplish hydrogen production in the model an electrolyser cell was implemented based on the SOEC version described in theory section 2.5. Desalinated water is supplied by the plant from a external water source at ambient conditions of 1 bar and 15 °C. Which adds to the benefit of constructing and operating NPP's

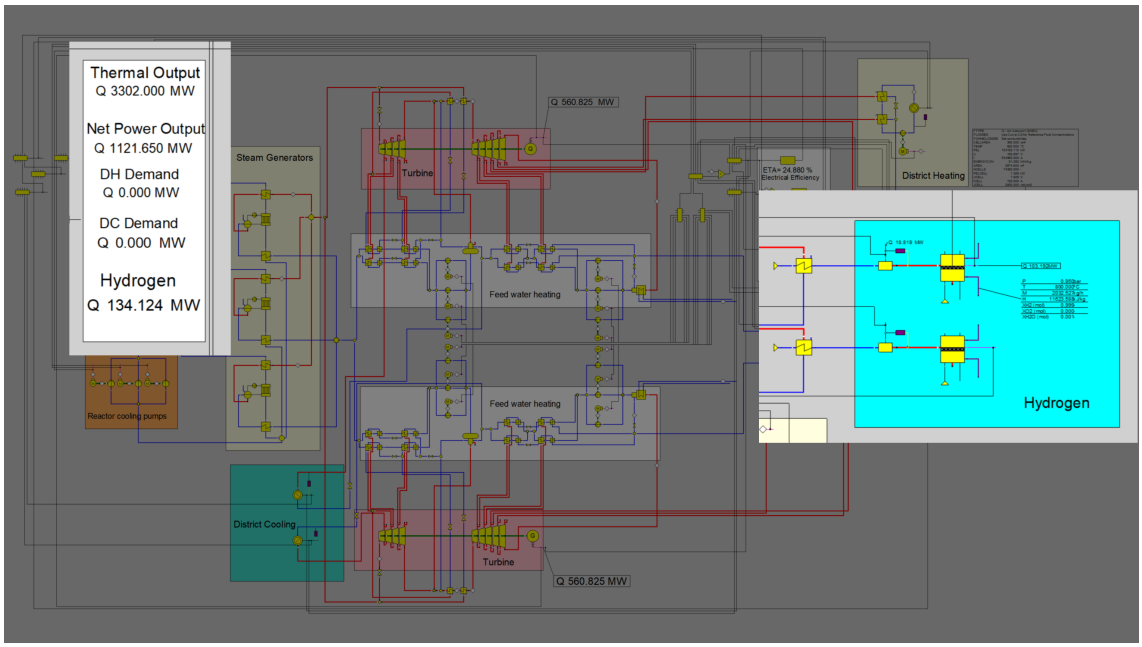


**Figure 3.4:** Implementation of hydrogen production and electrolysers to the NPP

close to natural water sources of abundance such as the sea. To ensure that the water entering the electrolyser is at the correct operating temperature it goes through a two step heating process. Firstly, to bring the desalinated water up to saturation temperature hot steam from the turbines are extracted at 1 bar and 115 °C to be utilized in an heat exchanger. The second step is to use an electric boiler, which is modelled by a heat injector component, to heat that steam up to operating conditions of 800 °C. The condensate from the heat exchanger is pumped back before it enters the condenser. These components are highlighted in blue in figure 3.4.

When modelling the hydrogen production a few aspects were needed to be taken into account to calculate the amount of hydrogen being produced from the model. Firstly Faraday's laws of electrolysis describes the relation between the current supplied through the electrolysis cell and the amount of substance liberated according to equation 3.1.

$$n = \frac{Is}{Fv} \tag{3.1}$$

Where:

· n = amount of substance (in moles) produced at the electrode

· I = current in amperes

· t = time in seconds

· F = Faraday's constant ( 96,485 C/mol)

· v = number of electrons transferred per ion or molecule formed

The conversion rate between the electrical input of the electrolyser and the energy output of the produced hydrogen is calculated by equation 3.2.

$$\eta_{electrolyser} = \frac{E_{H_2}[MW]}{P_{el}[MW]} \tag{3.2}$$

### 3.1.5 Case 4 - Combined operation

A combined operation where all three energy utilities are produced simultaneously is then conducted for three cases of utility demand 50, 100 and 150MW to analyse how the performance of the NPP is affected.

## 3.2 Techno-economic evaluation

This section describes the equations and calculations that evaluate the economical viability of each case. Investment costs for new components as well as revenue changes from the different energy utilities are taken into account and described in this section. Note that these economical calculations only take into account the new installations required compared to the original plant.

### 3.2.1 General equations

The calculations for profitability can be generalized through the following equations. Taking into account component investment costs, component instillation costs, revenue gains from selling newly implemented energy utilities and losses from not producing as much electricity as the reference case. The components investment cost is specific for each individual component and are described in subsequent sections 3.2.2-3.2.4, where as the remaining values are describe generally below. The specific values used for each new energy utility are summarized in Appendix C.

Equation 3.3 takes into account installation costs, material costs and piping costs to name a few. This value is there to encapsulate all these costs which are relevant when retrofitting or building a new power plant. The generalized equation which can be used for all subsequent components is shown below. The cost for installations is dependant on the number of new installations $N_n$ and the cost for each of those new installations $C_{NewMatch,n}$, where $n$ indicates the specific component.

$$C_{Installation,n,tot}[SEK] = N_n \cdot C_{Installation,n}[SEK/unit] \tag{3.3}$$

The annualized investment cost is described by equation 3.4 which is a summarization of the investment cost specific for a component and the installation cost for said component. These costs are then annualized with regards to the Annuity factor (AF) described in equation 3.5. In this equation $i$ refers to the interest rate of 5% and $l$ equals the lifetime of the equipment,30 years.

$$C_{investment,n}[SEK/year] = AF(C_n[SEK] + C_{newmatch,n,tot}[SEK]) \tag{3.4}$$

$$AF = \frac{i(1+i)^l}{(1+i)^{l-1}} \tag{3.5}$$

The total annualized investment cost for all new installations are then summarized in equation 3.6. A constant for increased costs associated with higher levels of security at a NPP compared to a conventional CHP plant is also taken into account denoted $\%_{NPP}$. In the results two different values of this constant is used to compare two cases, a retrofit of a NPP and a new NPP. The increase for a retrofit scenario is higher than that of a new plant, being a 200% increase compared to a 5% increase. This is due to the increased planning, safety measures and reconstructions necessary to ensure a safe and correct retrofit compared to a new plant production.

$$I_{tot}[SEK/year] = \sum C_{investment,n} \cdot \%_{NPP} \tag{3.6}$$

The Annual Net Profit (ANP) is then calculated by equation 3.7, based on the aforementioned investment costs and the losses and gains made from selling the electricity and secondary energy utility produced at the plant. $R$ equals the revenue and $I$ equals investment in the following equations.

$$ANP[SEK/year] = R_{gain,utility}[SEK/year] - R_{loss,el}[SEK/year] - I_{tot}[SEK/year] \tag{3.7}$$

Where the revenue loss from reduced electricity generation is calculated in equation based on the difference of electricity generated for the reference case and the investigated case to represent the potential market loss for electricity distribution. As the market for electricity and therefore its spot prices differ based on seasonal variations, (especially in Sweden), a weighted fraction of the electricity produced for both the reference case and the additional energy utility cases is made towards the winter months. In the modelling work 70% of the electricity is produced during the winter months which are represented by 4380 hours. The price of electricity is also kept constant for all cases however with a distinction between winter and summer prices being at 54.46 and 22.15 öre/kWh. These are chosen according to the annual average according to Nordpool [27]. This revenue split is seen in equation 3.8 as the indices *winter* and *summer*.

$$R_{loss,el} = R_{ref,el,(winter)} + R_{ref,el,(summer)} - R_{utility,el(winter)} + R_{utility,el,(summer)} \tag{3.8}$$

Revenue in a generalized fashion for the investigated cases is calculated according

to equation 3.9 whether it is the electriciy produced or the heat delivered, $P_{el}$ or $Q_{utility}$.

$$R_{utility} = P_{el}/Q_{utility} \cdot h_{operating} \cdot x_{summer/winter} \cdot Price_{summer/winter} \tag{3.9}$$

A sensitivity analysis where the average price for each utilities increases and decreases by 10%. was also conducted to analyse how this change affects the profitability of the implementation.

The ANP for the cases described in sections 3.1.2-3.1.4 and their energy demands is compared to the amount of steam being extracted for each specific case.

Finally the Pay Back Period (PBP) was calculated according to equation 3.10.

$$PBP = \frac{\sum C_n \cdot \%_{NPP}}{R_{utility} - R_{loss,el}} \tag{3.10}$$

### 3.2.2 Case 1 - District heating

The specific calculations needed for the DH case are presented in this section, highlighting the investment cost of the components introduced when producing DH as well as specifics of calculating the revenue gained from distributing said produced DH. All calculations are based on the DH demand as this impacts the amount of profit from distributing DH, the losses from not delivering as much electricity as the reference case and the investment costs that will be necessary to carry out either a retrofit or investments into a new plant. This value is ranged from 10 to 200MW in the modelling work as described in section 3.1.2.

The cost of investment for the new heat exchangers is estimated using equation 3.11 where the price is dependent on heat exchanger area. The total area needed to perform the heat exchange is calculated by equation 3.12 where $U$ $[W/m^2 \cdot K]$ is the overall heat transfer coefficient and $\Delta T_{ln}$ is the logarithmic mean value of the temperature difference over the heat exchanger. $U$ is set as 2 $[W/m^2 \cdot K]$ in all of the DH scenarios. $Q_{HX}$ is the heat transfer over the exchanger and is derived from the modelling work dependant on the DH demand.

$$C_{newareaHX}[SEK] = \sum Area_{newHX}[m^2] \cdot C_{areaHX}[SEK/m^2] \tag{3.11}$$

$$Area_{newHX}[m^2] = \frac{Q_{HX}}{U \cdot \Delta T_{ln}} \tag{3.12}$$

The investment cost calculations for the pumps needed in the DH case is dependant on the power each new pump needs to deliver. Equation 3.13 is based on the work done by Shamoushaki, Nikman, Talluri and Manfrida [28]. All correlations can be seen in [28].

$$C_{Pump}[SEK] = \sum_{n} log(\dot{W}_p) + a(\dot{W}_p)^2 + b(\dot{W}_p) + c \tag{3.13}$$

The constants in the pump cost equation are presented in table 3.1.

**Table 3.1:** The coefficients of Equation 3.13 for centrifugal pumps.

| **Equipment** | **a** | **b** | **c** |
|---|---|---|---|
| Pump | -0.03195 | 467.2 | $2,048 \cdot 10^4$ |

To more accurately reflect the yearly variation of DH demand, a greater share of generation is allocated to the winter months, when heating needs are higher. This seasonal adjustment also affects overall economics, as the costs of distributing electricity and heat vary between winter and summer due to differences in demand. As for the electricity demand the DH demand is also weighted with 70% of the demand being supplied during the winter months 4380 hours. The DH prices are set at 20 and 10 öre/kWh for winter and summer respectively. The revenue gained from selling DH utility is calculated by equation 3.14. Where each revenue can be derived from the generalized equation for revenue 3.9.

$$R_{DH} = R_{DH,winter} + R_{DH,summer} \tag{3.14}$$

### 3.2.3 Case 2 - District cooling

For the DC case the new addition of calculations that was needed were that of the investment cost for the absorption chillers. Modifications to the calculations

regarding revenue decrease and increase were made as to account for cooling utilities instead of heating utilities and the change in price and demand. There was however no distinction between winter and summer demand or prices as the reasoning of a constant industrial cooling demand is made.

The cost for the absorption chillers was calculated from equation 3.15 which was based on the work done by Nérot, Lamaison, Baviére, Lacarriére and Mabrouk [29]. These calculations describe the investment cost as a function of the DC demand $Q_{DC}$. The rate of exchange between EUR, USD and SEK are tabulated in Appendix C.

$$C_{AC}[SEK] = 1458\,€kW^{-1} \cdot (€ - SEK) \cdot Q_{DC}[kW] \tag{3.15}$$

### 3.2.4 Case 4 - Hydrogen production

In the hydrogen production model components used and therefore needed to be accounted for in the investment costs are the electrolyser, heat exchanger and electric boiler. The investment cost for the heat exchanger is calculated in the same way as in equation 3.4. The investment cost for the electric boiler (EB) which superheats the steam is calculated based on figure 3.5.

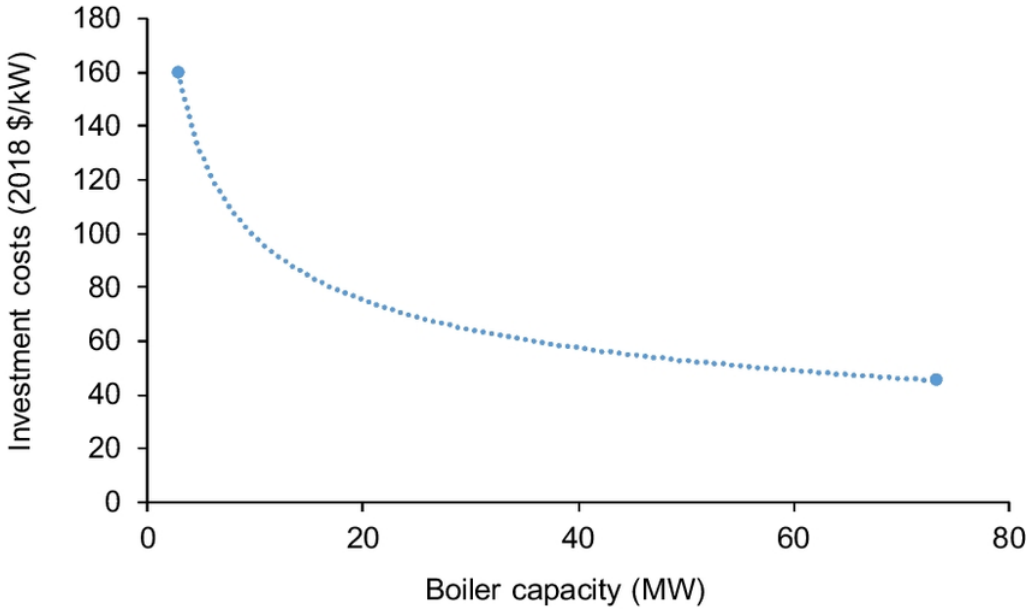


**Figure 3.5:** Cost relation between the electric boiler capacity and the investment cost.

This figure is adapted from the work by Zuberi, Hasanbeigi and Morrow [30]. Which relates the sizing of the electric boiler to its investment cost.

The investment cost of the electrolyser is based on the report from the Institute for Sustainable Process Technology and their report on Next Level Solid Oxide Electrolysis. In their report they conclude a total investment cost of 4800 EUR/kW for a 2020 scenario which could be lowered to around 1200 EUR/kW in 2030. As this report aims to give insight to the possibilities of new and future investments into nuclear energy the 2030 case was chosen for cost calculations.

$$C_{Electrolyser}[SEK] = 1200[€/kW] \cdot (€ - SEK) \cdot P_{el,Electrolyser}[kW] \tag{3.16}$$

The cost of hydrogen was estimated based on the reports from the European Hydrogen Observatory [31] which is part of the European commission. They present hydrogen production costs via electrolysis with a direct connection to a renewable energy source that varies from 4.13EUR/kg to 9.30EUR/kg, with and average for all countries being 6.61EUR/kg. In equation 3.17 the total mass flow rate of hydrogen produced by NPP is denoted $\dot{m}_{H_2}$.

$$R_{H_2}[SEK/yr] = \dot{m}_{H_2}[kg/yr] \cdot Price_{H_2}[€/kg] \cdot (€ - SEK) \tag{3.17}$$

# 4

# Validation of reference case

This section presents the validation made for the reference case in terms of input and output data against published literature. The model made for reference and validation is inspired by the reactors at Ringhals, R3 and R4 close to Varberg, Sweden. As the subsequent implementations and analysis made for the new energy utilities are all made based on the performance of the reference case the validation of this model is most important. This section will only highlight specific values of interest throughout the model. For a full list of data and stream values see Appendix A. The following table highlights the comparative values of reference data gathered from literature published by Vattenfall and their operation at Ringhals 3 and 4 [26], [25].

**Table 4.1:** Stream Data for Reactor and Steam Cycle

| | **Reference model** | **Ringhals 3** | **Ringhals 4** |
|---|---|---|---|
| **Reactor data** | | | |
| Thermal reactor power [$MW_{th}$] | 3302 | 3135 | 3292 |
| Net power output [$MW_{el}$] | 1130 | 1064 | 1130 |
| Total efficiency [$\eta_{tot}$] | 32.507 | 32.3 | 32.3 |
| Operating pressure [$MPa$] | 15.5 | 15.5 | 15.5 |
| Cooling water flow rate [$kg/s$] | 16534 | 13778 | 14223 |
| Inlet temperature [°C] | 289 | 282.8 | 282.7 |
| Outlet temperature [°C] | 323 | 323.7 | 323.9 |
| **Steam generator data** | | | |
| Steam flow [kg/s] | 1767 | 1670 | 1726 |
| Steam pressure [MPa] | 6.3 | 6.3 | 6.3 |
| Steam temperature [°C] | 279 | 276 | 276 |
| Feed water temperature [°C] | 232 | 221 | 203 |
| **Steam turbine data** | | | |
| Steam flow [kg/s] | 2x867 | 2x760 | 2x760 |
| Steam pressure inlet HP [MPa] | 6.3 | 6.3 | 5.9 |
| Steam temperature inlet HP [°C] | 279 | 279 | 278 |
| Steam pressure outlet HP [°C] | 0.7 | 0.7 | 0.7 |

| | **Reference model** | **Ringhals 3** | **Ringhals 4** |
|---|---|---|---|
| Steam temperature outlet HP [°C] | 165 | 165 | 165 |
| Steam pressure inlet LP [°C] | 0.46 | 0.46 | 0.46 |
| Steam temperature inlet LP [°C] | 260 | 260 | 260 |
| Steam pressure outlet LP [°C] | 0.004 | 0.004 | 0.004 |
| Steam temperature outlet LP [°C] | 29 | 29 | 29 |

The simulated result values from the reference model show a small margin of deviation compared to literature values, with most results differing by less than 3%. However, notable differences around 13% are observed for the cooling water flow rate, feedwater temperature, and live steam flow rate. These differences may stem from simplifications made in representing the PWR reactor using a heat consumer, as well as from assumptions about the temperature and pressure conditions at which high-pressure steam extractions occur. If steam is extracted at higher temperature and pressure levels than in the reference plant, the returning feedwater would reenter the steam generator at a higher temperature, potentially affecting both the steam generation rate and the cooling water requirements. While these differences may slightly affect the overall efficiency and output predictions, the model still provides a reasonable approximation of PWR behaviour.

# 5

# Results and Discussion

This section presents the results and the accompanying analysis for all different cases of DH, DC and Hydrogen production. These include the technical assessments on how the new technology implementations impact production and efficiency of the NPP as well as the economical analysis on how new investments will impact the NPP's revenue.

## 5.1 Plant performance evaluation

By extracting a percentage of the steam from the turbine to heat the returning DH water the available amount of steam useful for electricity generation is reduced. In figure 5.1 the results on how the electrical efficiency, total efficiency and power to heat ratio of the NPP is affected by a percentage of steam extraction is presented.

As expected, a decrease of electricity generated reduces the electrical efficiency as the thermal output from the reactor is kept constant. The electrical efficiency decreases linearly as seen in figure 5.1 in relation to increased steam extractions. For the simulated demands which extracts up to 32.5% of the available steam the electrical efficiency reduces from 32.5 to 28.8%. By reducing the amount of steam available for expansion over the turbine the enthalpy difference reduces resulting in a lower amount available for electricity generation. However, because you recover more of the fuel's energy as usable heat, the total efficiency improves. As this is the case the total efficiency increases quicker than the decrease of the electrical efficiency. Additionally, when more steam is extracted, the power-to-heat ratio decreases. This is because less power is produced for each unit of heat delivered. As the amount of extracted steam gets very large, the ratio gets closer to zero, and the curve starts to flatten, as:

$$\lim_{Q_{\text{useful}} \to \infty} \alpha = \lim_{Q_{\text{useful}} \to \infty} \frac{P_{\text{net}}}{Q_{\text{useful}}} = 0 \tag{5.1}$$

Similar trends for plant performance can be seen in figure 5.2 for the implementation of DC. Electrical efficiency is decreased while total efficiency increases. Compared to the DH case the amount of steam extracted is higher to achieve the same increase of performance in total efficiency. To achieve the same total efficiency of the NPP the DC case needs to extract around 13% compared to the DH case which only needs to extract around 7.5%.

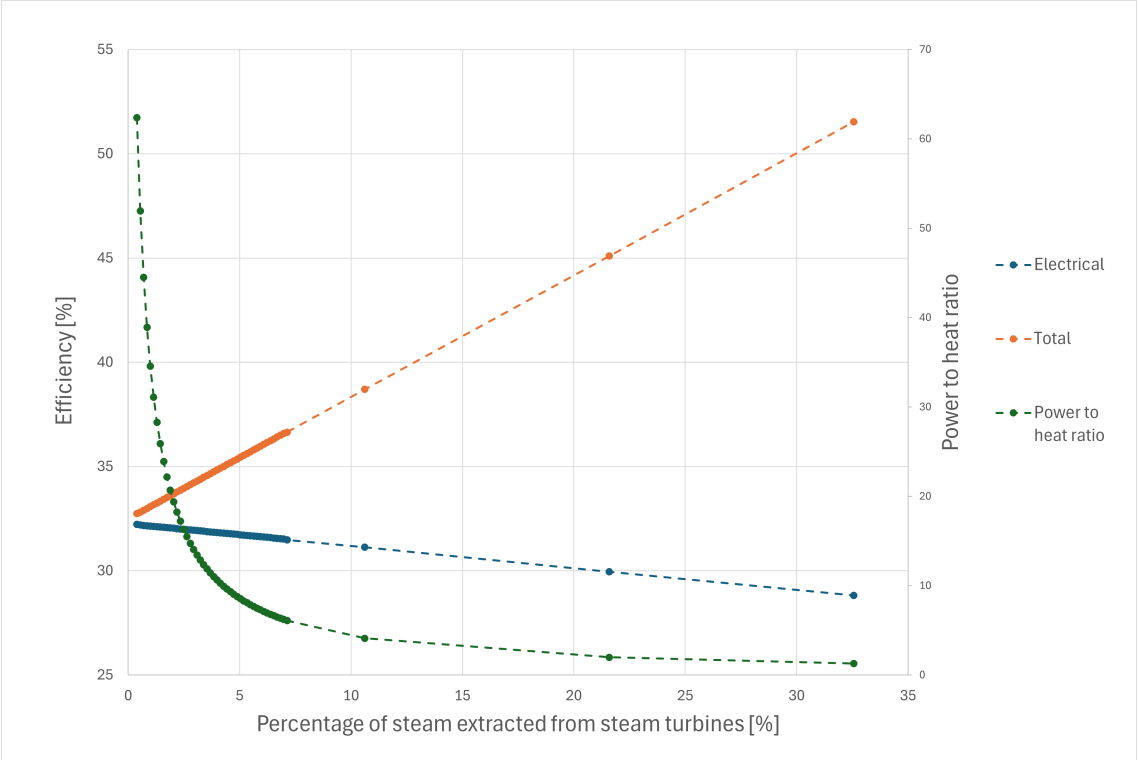


**Figure 5.1:** Performance parameters of the NPP by implementing DH utilities and the steam extractions required, ranging from 0 to 750 MW of DH

When either supplying DH or DC from a steam cycle, the point of the steam extractions significantly affects the total plant efficiency. If steam is extracted from a HP turbine stage, it is at high temperature and pressure, meaning it possesses high exergy and a greater potential to generate electricity. Extracting this high-quality steam reduces the amount of energy available for power production, resulting in a substantial loss in electricity generation. In contrast, extracting steam from a LP turbine stage occurs later in the cycle when the steam is at lower temperature and pressure. This steam has lower exergy and thus less potential for electricity generation. As a result, the impact on the turbine's electrical output is smaller, and the overall system experiences a smaller electrical efficiency loss. Therefore, as the total efficiency expressed in equation 2.8 is dependent on the electrical output, thermal output and thermal input, a larger decrease in electrical output will result in lower

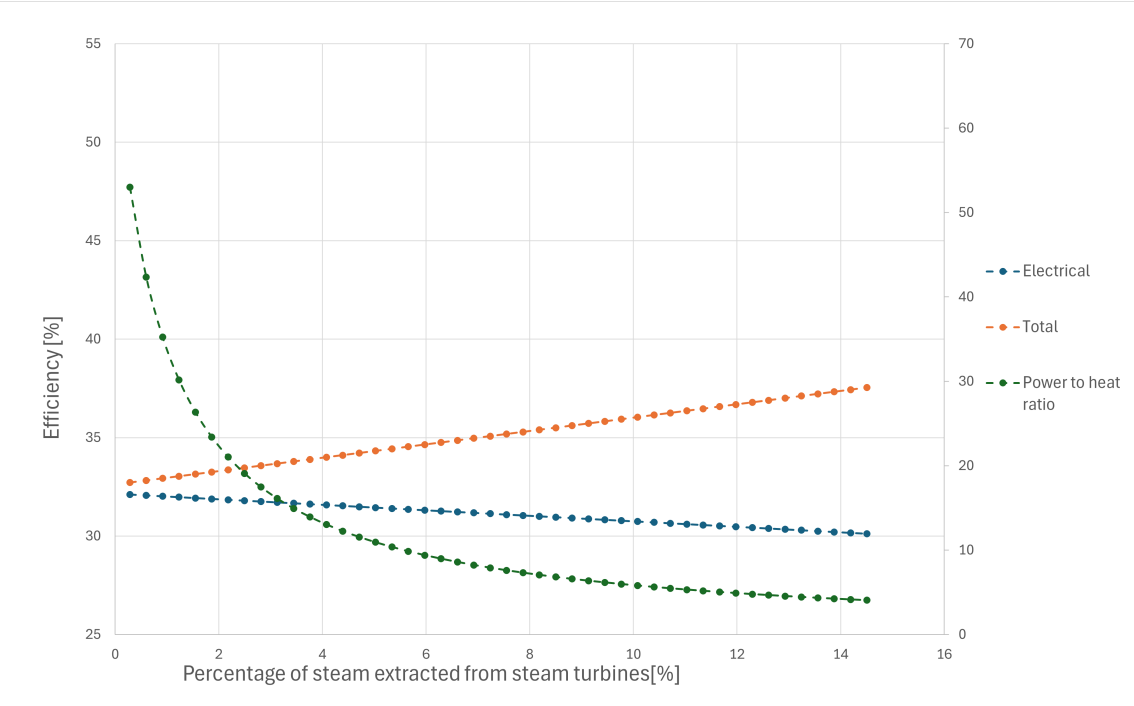


**Figure 5.2:** Performance parameters of the NPP by implementing DC utilities and the steam extractions required, ranging from 0 to 470 MW of DC

total efficiency as the thermal output and input is kept constant. Therefore the case of producing DC utilities which extracts steam from the HP turbine will result in a lower total efficiency at the same amount of extracted steam or utility demand as for the DH case which extracts steam from the LP turbine. This is supported by figure 5.1 and 5.2 which showcases that a larger amount of steam is needed for the DC case compared to DH to achieve the same performance increase.

Another aspect that affects the performance of the DC case is that the model includes heat consumers as representatives for the real applications of absorption chillers. However, if evaluating the absorption chillers were to be done in more depth the difference in COP would also affect the required amount of steam extraction. Typically absorption chillers have a COP between 0.6 and 1.2, meaning they require significantly more thermal energy to deliver a given amount of useful cooling compared to direct heating used in DH heat exchangers. Furthermore, absorption chillers introduce greater thermodynamic irreversibilities and internal losses, making them less exergy-efficient than direct heating systems. As a result, more high-quality steam must be extracted to provide the same useful energy output. Therefore, to achieve the same gain in total efficiency, more steam must be diverted to the absorption chillers than to DH.

Compared to the cases of cogeneration of DH and DC, the performance, in terms of total efficiency, does not increase when increasing the amount of hydrogen produced. The consumption of electricity to produce the required hydrogen is to large. These

relations are presented in figure 5.3 for electrical and total efficiency. This distinction is a result of the increased in house consumption of electricity needed to produce the hydrogen. Both the electrolyser and the electric boiler consumes electricity produced by the NPP to achieve their respective function. Table 5.1 showcases the conversion rate between electrical input and hydrogen output over the electrolyser for the different production cases. As the conversion rate is less than 1 for all cases, $P_{el}$ decreases faster than the $P_{H_2}$ increases. The simulated conversion rates are distinctly lower than the standard for SOEC electrolysers at 70-80%.These values can be represented by $P_{net}$ and $Q_{out}$ in equation 2.8 for total efficiency, which results in the total efficiency decreasing.

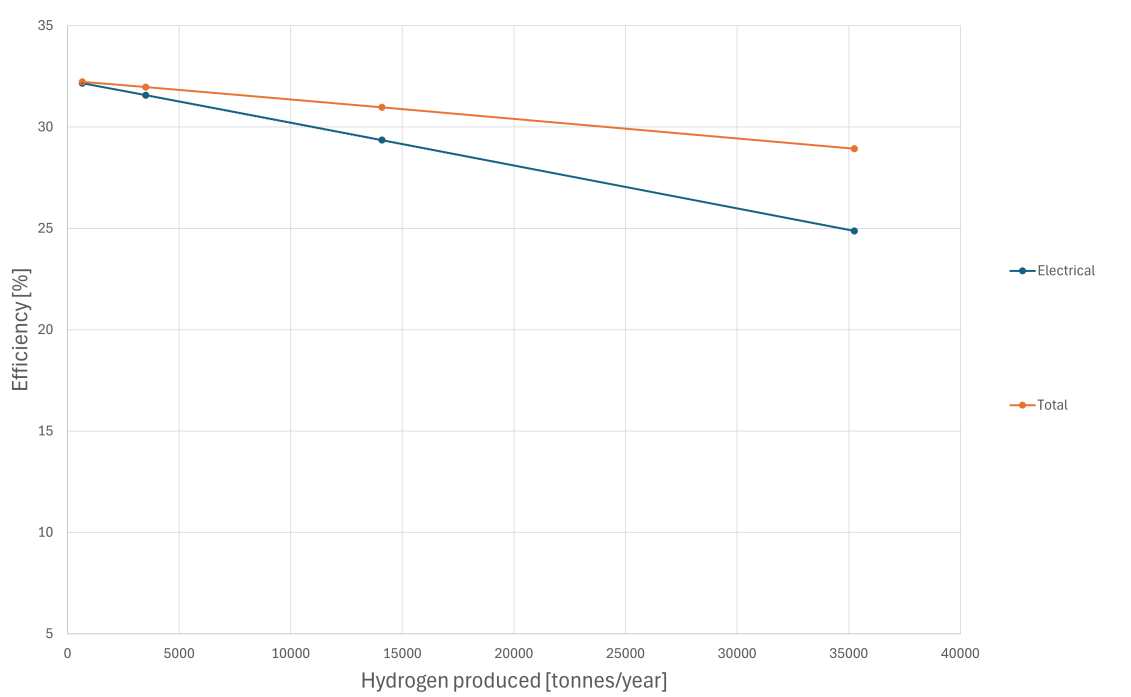


**Figure 5.3:** Performance parameters of the NPP by implementing Hydrogen production to the NPP, ranging from 0 to 134 MW of Hydrogen

**Table 5.1:** Simulated conversion rate over the electrolyser

| **Electrical input [MW]** | **Hydrogen utility [MW]** | **Conversion rate [%]** |
|---|---|---|
| 3.52 | 2.53 | 71.88 |
| 19.81 | 13.36 | 67.43 |
| 81.59 | 53.61 | 65.71 |
| 206.38 | 134.12 | 64.99 |

The final configuration implement all three energy utilities in a combined model which operates under the pretence that all utilities are produced equally. The performance impact of the NPP can be seen in figures 5.4 and 5.5. These figures give the indication that by producing all utilities the gain in increased total efficiency by utilizing the steam extractions is less than that of the individual cases, mainly because the electricity consumption of producing hydrogen is too high. The conclusion can then be made that implementing DH by itself yields the highest increase of total efficiency per MW of installed utility capacity. If 150MW of each utility is

produced there is an increase of total efficiency from 32.5 to 35.5%. For this case we can also see that the total heat utilized from the steam is around 256 MW from figure 5.5.

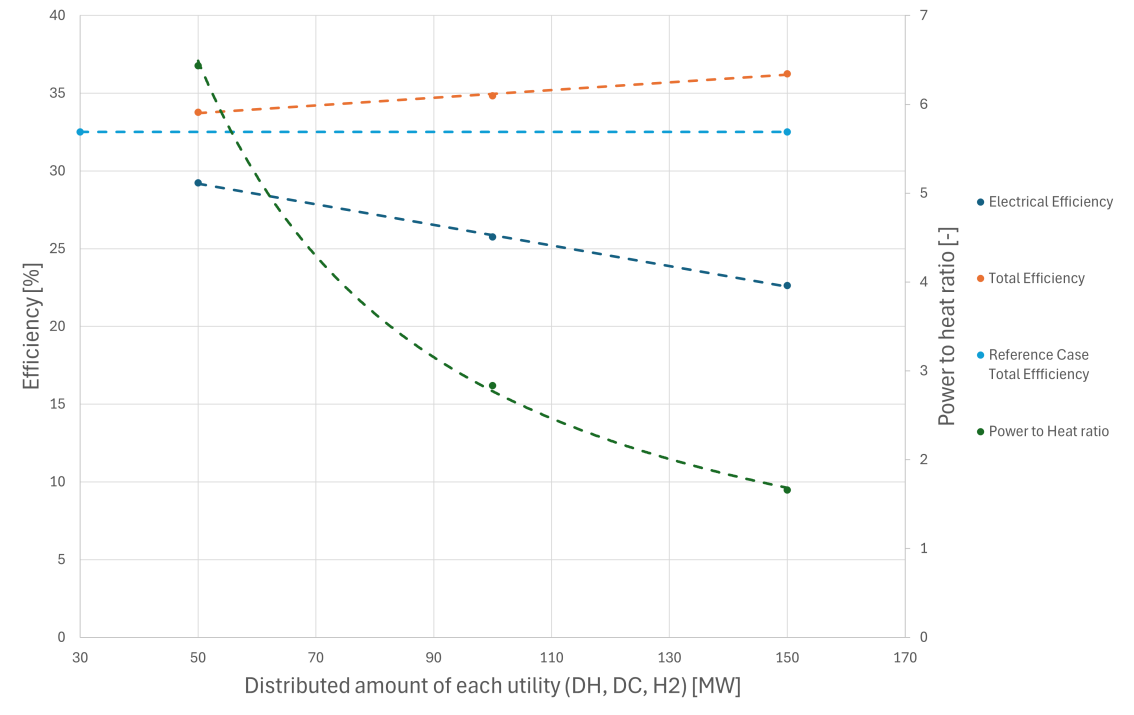


**Figure 5.4:** Performance parameters for implementing all three energy utilities, DH, DC and Hydrogen to the NPP, ranging from 0 to 12% steam extraction

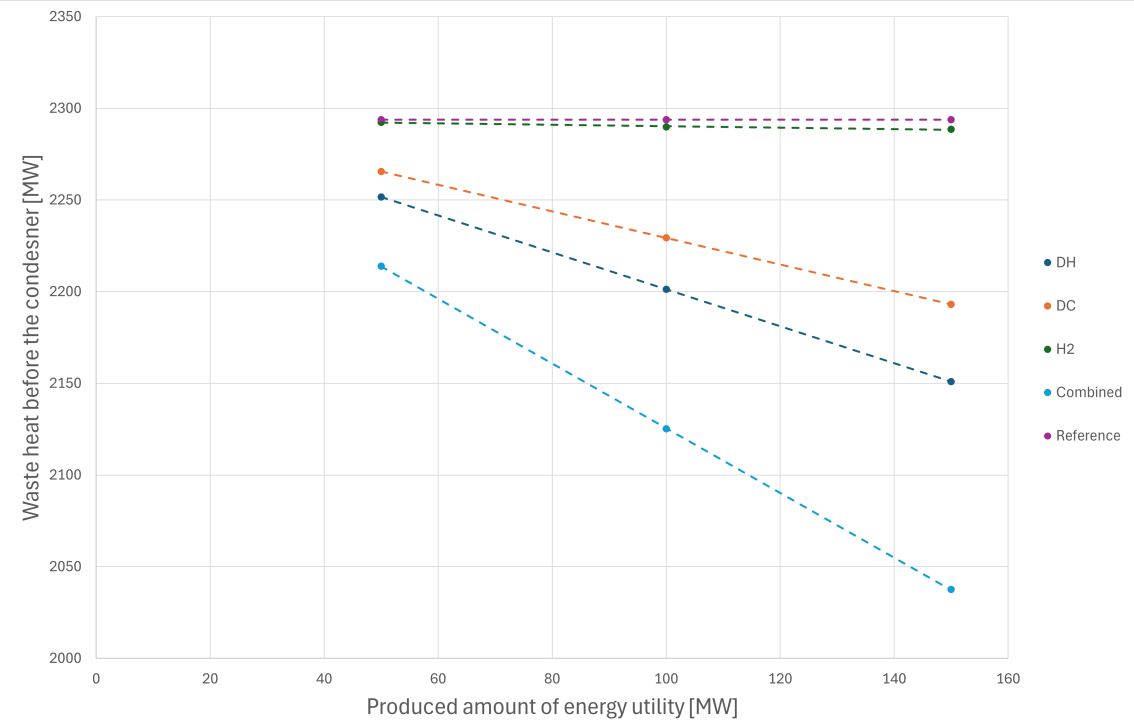


**Figure 5.5:** Waste heat left in the steam that enters the condenser dependent on which energy utility is implemented.

## 5.2 Economic evaluation

By diverting steam to produce DH as a second energy utility the new investment and revenues are shown in figure 5.6. In this figure five scenarios are presented to indicate how future electricity prices and heating prices could affect the revenue from implementing DH. As the additional heat delivered to DH exceeds the loss in electricity production, the overall gain favours DH production. This means that the revenue becomes more sensitive to changes in the DH price than to changes in the electricity price. The results shown in Figure 5.6 correspond to the retrofit scenario, which involves the highest investment costs. The new plant scenario is not included, as it primarily affects the required DH load for profitability. Specifically, it reduces the amount of DH needed to make the system economically viable.

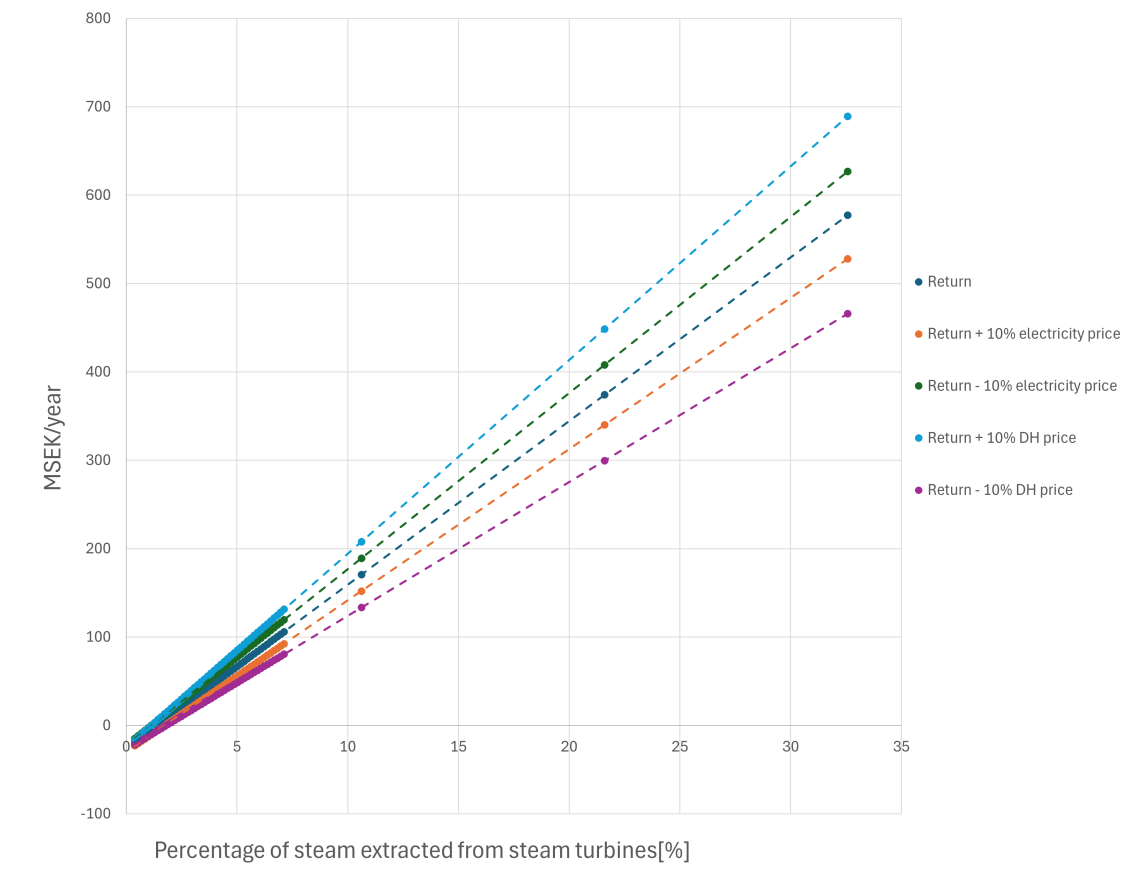


**Figure 5.6:** Revenue for implementing DH to the NPP based on electricity and heating prices in the ranges

Since the relation between plant performance and the percentage of steam extraction is linear as shown in the previous section, and all cases showed that significantly lower extraction rates were sufficient for positive revenue, the analysis was not extended beyond 15% steam extraction for the following cases. The following table and values are extracted from figure 5.6, shows the percentage of steam that must be extracted

in the model used in this thesis to reach the break-even point for the investment.

**Table 5.2:** Required amount of steam needed for DH utility to be profitable

| **Scenario** | **Extracted Steam** [%] | **DH** [MW] |
|---|---|---|
| Current prices | 1.42 | 40.39 |
| Electricity price 10% higher | 1.74 | 47.83 |
| Electricity price 10% lower | 1.14 | 34.01 |
| Heating price 10% higher | 1.14 | 34.15 |
| Heating price 10% lower | 1.81 | 49.44 |

Important to understand in these results is that the electricity price directly dictates the amount of revenue available based on the electricity generated. As the DH demand increases, the amount of electricity generated by the NPP is reduced. As the generated amount is less than that of the reference case as well as the price for electricity being higher then the DH price the operator of the NPP is losing potential revenue. Since the conversion rate for extracted steam is greater than one for DH, this offsets the higher electricity price compared to that of DH. Furthermore, a larger amount of DH is required to compensate for both the loss in electricity revenue and the investment costs, with the increased revenue from DH helping to bridge this gap. Every kilogram of steam flowing through the turbine firstly generates substantial amount of electricity before it it extracted for heat uses. The amount of electricity lost because of this is therefore small compared to the amount of heat available for every kilogram of steam. The thermal efficiency is generally a lot higher then the electrical efficiency for CHP's. The opposite is true for a decrease in electricity price, resulting in less DH utility necessary to cover investment costs and losses in electricity revenue. The same argument can be made from increasing or decreasing DH prices. Expect here the increase of DH price result in less DH being needed, as the revenue increases and vice versa for a decrease in price.

From figure 5.1 and 5.6 there is a clear trend that by increasing the amount of DH utility delivered by the NPP there are positive performance and economic results, however, it is important to take into account the limitations on how much DH utility that could be delivered. Otherwise the argument can be made "the more the merrier". For a retrofit scenario where additional extractions are made to the already established system, the technical and feasible operation of the plant needs to be understood. Diverting a large portion of steam from the turbine to supply DH in a NPP can introduce several operational challenges. Turbines, reactor, feedwater systems, pumps, valves and heat exchangers are designed to operate at certain conditions. Decreasing the amount of steam available for expansion may lead to unstable turbine operations, increased mechanical stress, and reduced efficiency for different components. However as most NPP's today operate at some intervals of partial load the extractions of steam around 10% should not deem problematic. It is more a question of having the appropriate extraction available in regards to pressure and temperature. It may also limit the plant's ability to maintain required safety margins, especially during load changes. These limitations are not applicable for

a new plant scenario as the turbines can be adapted and designed for a specific purpose and specific extractions.

Limitations can also be seen from the market perspective as the market may be saturated in regards of suppliers. Municipally owned companies may already have invested in the DH market supply of a city, industry or area. DH is a natural monopoly as the infrastructure supplying the DH is usually owned by specific companies. As this is the case new investments would also have to be made to deliver the DH.

For the district cooling case, where steam is extracted from the HP turbine to supply high temperature heat to the absorption chillers an analysis is done for two different cases. These two cases represent the two scenarios where investments for DC is done as either a retrofit of a already operating NPP compared to a completely new installation. As this thesis work only investigates how new installations affect a NPP the costs of investment for a new NPP are not covered in this report. The only difference between these two scenarios is the investment cost increase made to account for components installed in at a NPP. The constant $\%_{NPP}$ is for the retrofit scenario equal to 100% and for the new plant equal to 5%.

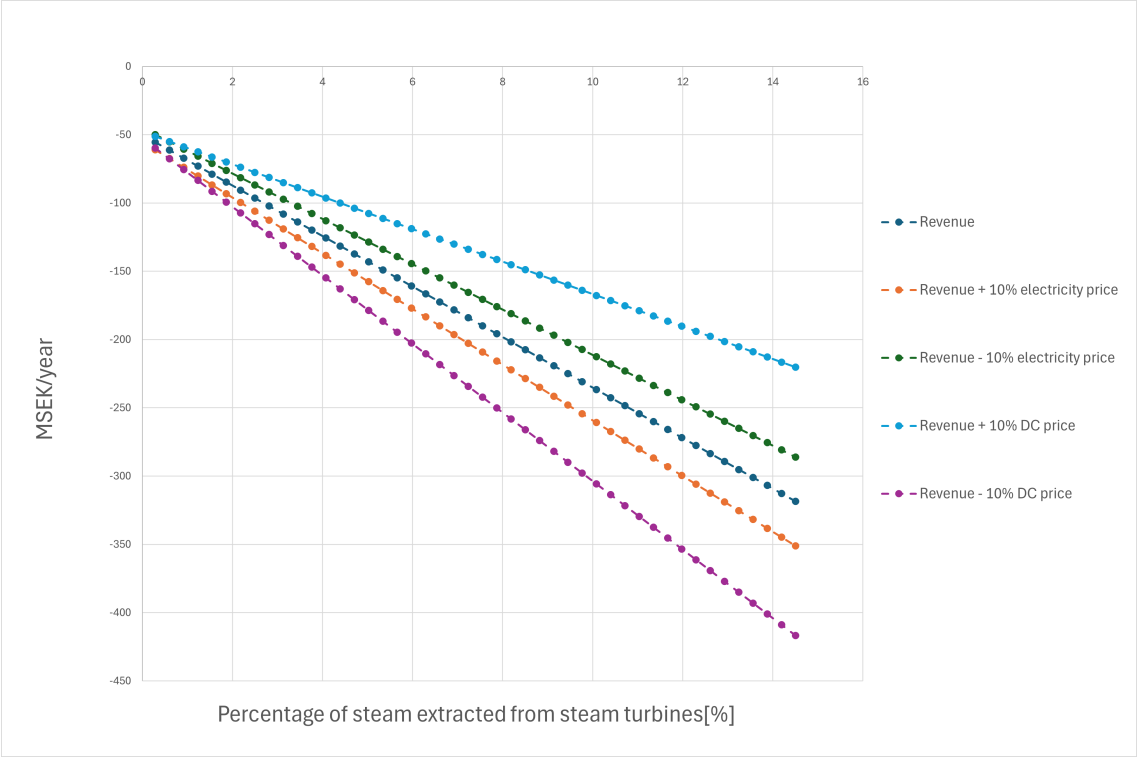


**Figure 5.7:** Revenue calculations and sensitivity analysis for implementing DC to the NPP based on current and future electricity and cooling prices, for a retrofit scenario.

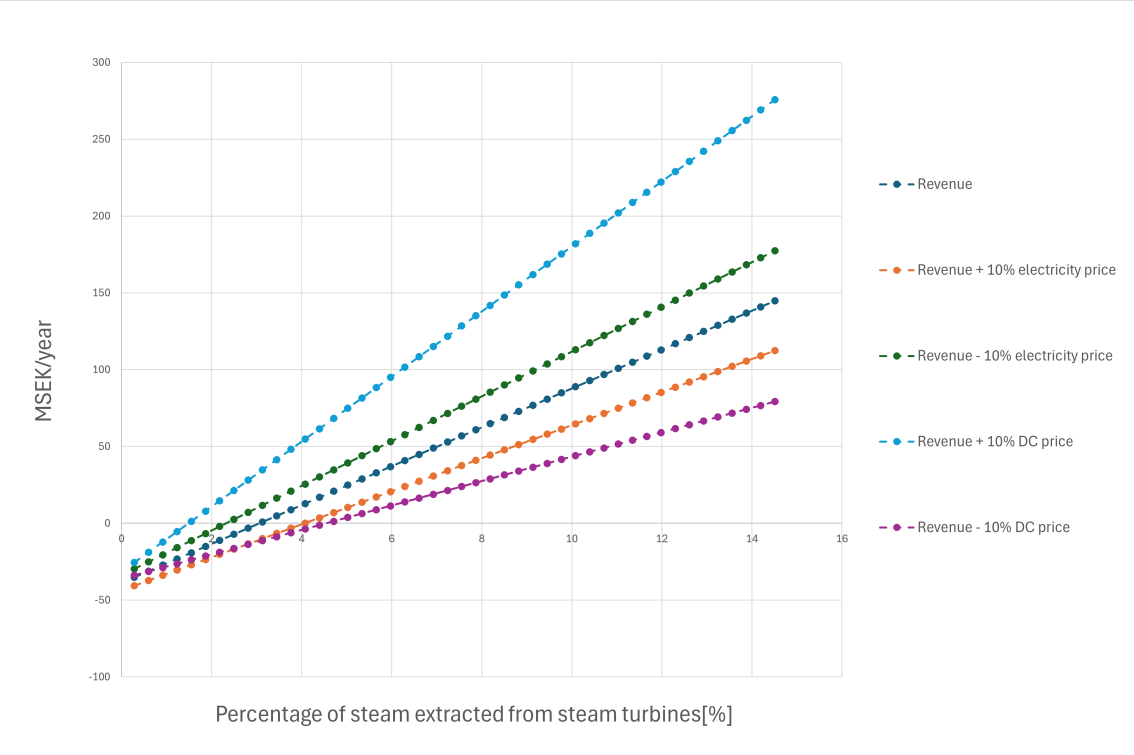


**Figure 5.8:** Revenue calculations and sensitivity analysis for implementing DC to the NPP based on current and future electricity and cooling prices, for a new plant scenario.

**Table 5.3:** Required amount of steam needed for DC utility to be profitable for a new plant scenario

| **Scenario** | **Extracted Steam [%]** | **DC [MW]** |
|---|---|---|
| Current prices | 3.06 | 107.88 |
| Electricity price 10% higher | 4.06 | 139.50 |
| Electricity price 10% lower | 2.32 | 84.54 |
| DC price 10% higher | 1.49 | 58.14 |
| DC price 10% lower | 4.55 | 154.88 |

As the total investment costs for the retrofit scenario is nearly double the amount for the new plant scenario the revenue gained from selling DC utility is not sufficient to make this profitable. This can be seen in figure 5.7 and 5.8. Attached to figure 5.8 is the required steam extraction percentage to reach the break-even point of the investment showcased in table 5.3. These values are for the new plant scenario as the retrofit is to expensive, making it impossible to be profoitbale based on the currently operating conditions of the plant. As was the case of the DH utilities, an increase of electricity prices and an decrease of DC prices would require a larger portion of steam to be extracted to produce DC. Which also means that a decrease of electricity price and increase of DC price would result in less DC utility needed to make profit.

The revenue compared to the amount of hydrogen produced annually is shown in figure 5.9 and combined with table 5.4 the break even point for the models operational conditions are shown. If the conversion rate would increase to industry standard for SOEC's around 70-80% the amount of electricity required would decrease, resulting in lower losses from not distributing electricity, which would increase the total revenue and lowering the amount of hydrogen needed to be produced to make profit for all cases. So even if the electrical and total efficiency decreases when implementing hydrogen as shown in figure 5.3, the high price for hydrogen requires comparatively a low amount utility produced to compensate for losses and investments, making the choice of implementing hydrogen to a NPP still an attractive option as seen in figure 5.9.

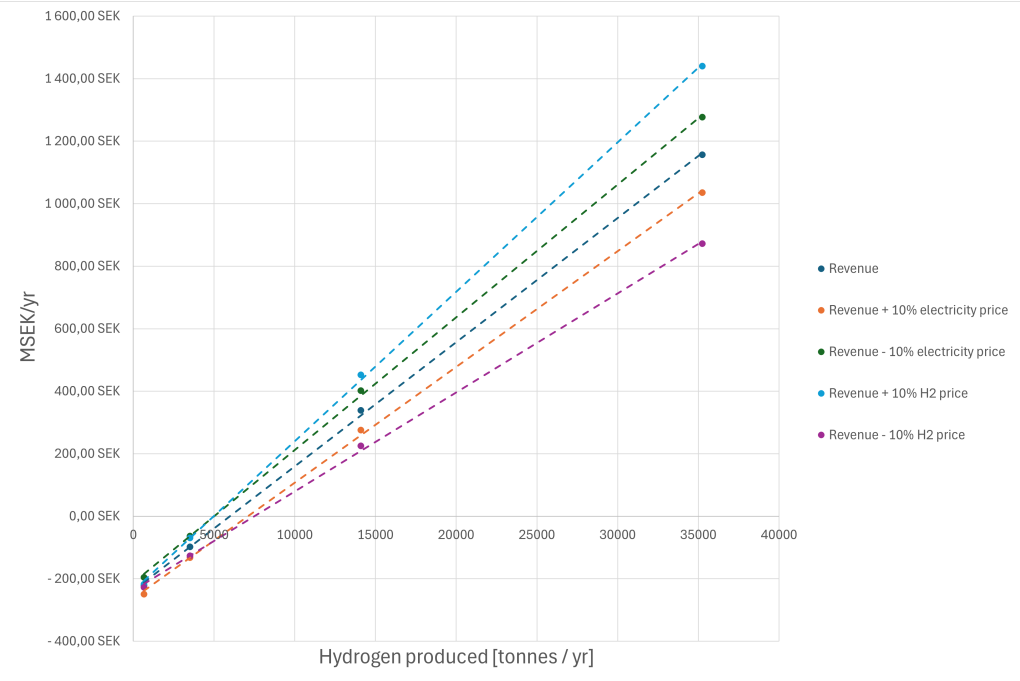


**Figure 5.9:** Revenue calculations and sensitivity analysis for implementing Hydrogen production to the NPP based on the current price of 241 öre/kWH and future electricity and hydrogen prices.

**Table 5.4:** Required amount of $H_2$ needed to make the different price scenarios profitable.

| **Scenario** | **Produced hydrogen[tonnes/yr]** | $H_2$ **[MW]** |
|---|---|---|
| Current prices | 5984 | 22.77 |
| Electricity price 10% higher | 7095 | 27.00 |
| Electricity price 10% lower | 5017 | 19.09 |
| $H_2$ price 10% higher | 4977 | 18.94 |
| $H_2$ price 10% lower | 7504 | 28.55 |

If these applications were implemented at the NPP there would still be limitations to what theoretical maximum the revenue could increase by producing hydrogen. Limitations based on demand and infrastructure directly dictates how much of the electricity produced that could be diverted to hydrogen production. There are strategies and goals set by governments to increase the fraction of hydrogen used in society compared to today which could increase demand. Sectors such as transportation, process industry and energy could all benefit by utilizing hydrogen in some form. The main issue around increasing the share of hydrogen used in these sectors would then be the infrastructure around the usage. The difficulties of transporting the produced hydrogen to the consumer is one major issue. Hydrogen can be transported in several different forms, depending on application and distance from production site. One of the most common methods is compressed hydrogen gas, stored at high pressures. This form is widely used for fuelling stations and short to medium distance delivery by tankers or pipelines. For longer distances, especially across oceans and for global trade, liquefied hydrogen is used. In this case, hydrogen is cooled to cryogenic temperatures to increase its energy density, though this requires significant energy input reducing the conversion rate further. Another method is the use of hydrogen carriers. Ammonia ($NH_3$) is one such carrier that can store large amounts of hydrogen and be transported using existing chemical infrastructure. The hydrogen can later be released through a cracking process, again requiring additional energy inputs. The most efficient method is to deliver hydrogen via pipelines. However, this requires investments in infrastructure and is limited based on the distance from the producer to the consumer. As this thesis has not investigated the cost accompanied with transport and infrastructure the profitability calculations are underestimated. Additional costs in these sectors would increase the amount of hydrogen required to remain profitable and revenue gained per MW of produced hydrogen.

Another aspect which impacts the results is to take into account at what amount of hours would the electrolyser really be profitable. The revenue calculations are based on the assumption that the model operates at full capacity and that the its operational 8760 hours of the year. As the price for hydrogen is determined to be significantly higher than that of the electricity price in these calculations the revenue gained from that energy utility will always result in increased total revenue. There could be a scenario where electricity prices would increase due to high demands,

low renewable generation and fuel price spikes combined with lowered hydrogen prices as the technology becomes more wide spread and better infrastructure is implemented. In these moments there could be hours when the electricity price is higher than that for hydrogen where producing only electricity would be the most profitable. The opposite could also be true for a scenario where there is a high penetration of renewables and low demands. Instead of shutting down the turbine as the merit order of generation dictates that the NPP generated electricity would not be profitable there could be a increase in hydrogen production. This excess hydrogen could then be stored through in either a compressed, liquefied or ammonia suspension state for later usage.

A economic assessment was not conducted for the combined model, as the previous individual cases demonstrated that sufficient utility production leads to positive revenues, which would likewise apply to the combined model. However, if a combined operation is not available and one energy utility should be considered figure 5.10 displays at what investment costs the different utilities become profitable. This graph could then be used to promote one utility dependent on the amount of investment that can be made. The argument can be made that for all sizes of investment the case of DH and the scenario of a NEW plant would be the most wise. By doing this the revenue is maximized while investment costs are kept as low as possible. Important however is to consider the limitations described in 5.1 before making a decision. If DH is not an option investments under 60 $MSEK/yr$ could be argued to be made into DC instead of hydrogen however these are still negative revenues making them unrealistic. Above 65 $MSEK/yr$ however hydrogen becomes more profitable then DC and is also a positive revenue.

Although the DH and DC cases may individually yield negative revenues at low demands, their combined operation can generate positive overall revenues. This is because DH and DC utilities often exhibit a complementary revenue relationship relative to the total utility produced. As seen in figure 5.6 and 5.8 they both indicate a positive relation in comparison to the amount of demand. In scenarios where an industry or city demands only a limited amount of one utility, such as low cooling or heating the NPP may appear unprofitable if assessed solely on that utility's performance. However, when the revenues from both heating and cooling are considered together, the combined system can achieve economic viability and improve the profitability of the NPP by effectively maximizing utility utilization as long as the combined demand is sufficiently high. Which also leads to increased performance. Since NPPs are typically located outside of cities and closer to industrial areas, it is more likely that both heating and cooling demands exist simultaneously rather than only one utility being needed, increasing the total amount of energy utility demand.

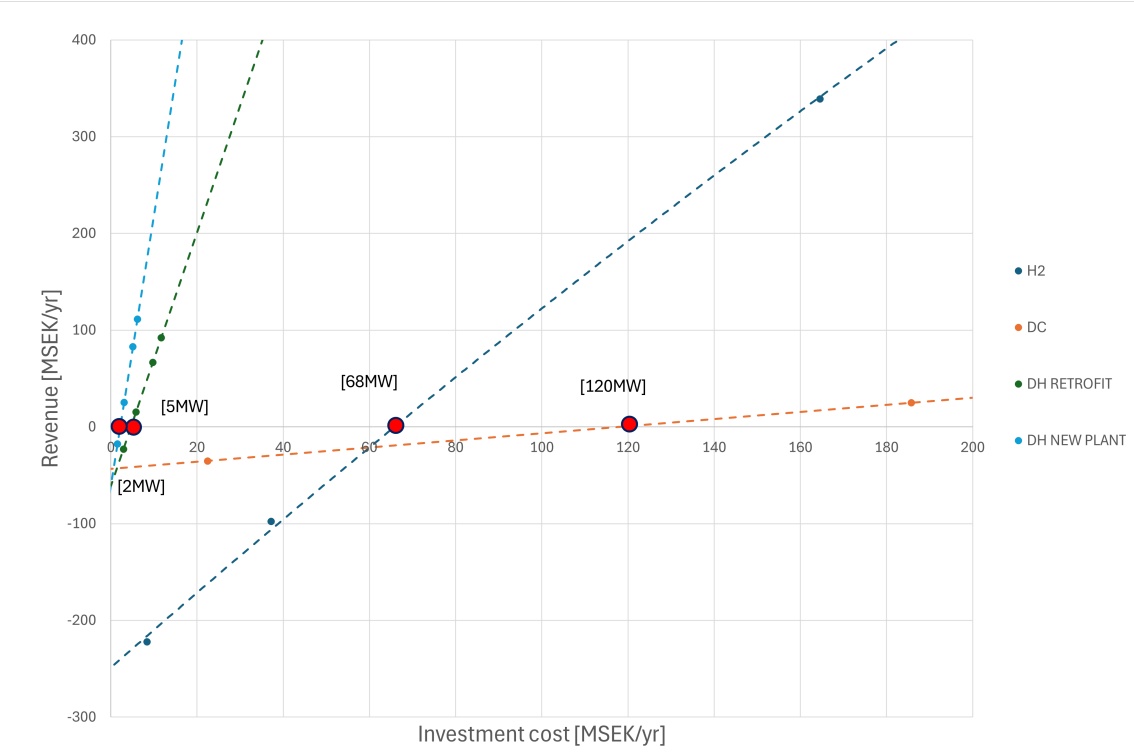


**Figure 5.10:** Comparing the different energy utilities and at what sizes of investment they would be profitable and recommended.

As we have seen in previous graphs and results the total efficiency generally increases when implementing multiple energy utilities. However, the amount of steam being extracted is relatively low resulting in up to 12-15% for a 5% increase in total efficiency and even lower extractions are necessary for profitability. As there are limitations to the size of demand, be it market share, technical or infrastructure, each of these utilities presented might have a maximum which is lower then expected. Therefore a interesting approach when it comes to a new plant scenario may be to investigate and develop small modular reactors (SMR) instead. As the net electrical power of these plants are significantly smaller then for the proposed model of $1130 MW_{el}$ the amount of steam produced by the steam generator is also significantly smaller. If the same utilities and demands were implemented on this type of reactor instead the percentage of steam being extracted would drastically increase, resulting in less waste heat being present after the turbines.

# 6

# Conclusion

After the simulation work, performance calculations and techno-economical calculations were done, this thesis can conclude that by implementing the energy utilities DH, DC and Hydrogen either separate, or in combination, the total efficiency, performance and economics of the NPP can be increased. There is a clear correlation between the increased integration of multiple energy utilities and improved performance, as the thermal output generated and delivered by the PWR is utilized more efficiently. There is less amount of waste heat left in the expanded steam before it enters the condenser, meaning that more of the thermal energy delivered by the PWR has been utilized to yield a positive energy utility. This thesis concludes that the energy utilities, DH, DC can be implemented to a NPP and will yield a total plant performance increase as well as increased revenue. Implementing a high-temperature electrolyser at the NPP results in a reduction in overall plant performance as the conversion rate over the electrolyser is >1, but can still generate positive revenues. For DH and DC the advancements made in total efficiency are larger than the decrease in electrical efficiency. For all three cases it is concluded that there is a linear relation between the amount of utility produced and the change in performance. The same linear relation is also derived from the techno-economical calculations made in this thesis, showcasing a positive gain in revenue when demand increases for all utilities. However, in all cases, there is a minimum required level of utility output needed to compensate for the investment costs and the associated loss in electricity revenue.

When extracting approximately 7.5% and 13% of the steam available for electricity generation for DH and DC respectively, the total efficiency of the NPP can be increased from 32.5% to 37%. It is also concluded that a positive revenue for these investment can be made at even lower extractions, at 1.42% and 3.06% based on current prices for electricity and heating. This would result in utility demands of 40.39 and 107.88MW for DH and DC respectively.

Based on a comparison of the utilities and the distribution levels required, this thesis concludes that implementing DH at a newly built NPP offers the highest revenue relative to investment. This finding also extends to performance, as DH enables more efficient utilization of waste heat compared to the other utility options.

## 6.1 Future work

Further development of both the modelling work and the economic assessment can be made. In the different models developed in *Ebsilon Proffesional* certain simplifications were made as to account for the limited components available for use. Most notably further work could be made for the case of DC as the absorption chillers referenced and for which the profitability calculations were made where not modelled for. The simplification of replacing the absorption chillers multiple components with heat consumers may affect the sizing of the steam extractions. To accompany for all the involved components further development of the Ebsilon model could be conducted, utilizing more components. Another approach would be to utilize a different simulation software such as Aspen HYSYS to further develop relevant components as to give a more detailed estimate of heat demands and energy balances. The same argument could be made for the hydrogen production case as more intricate modelling approaches could yield more accurate results in terms of sizing the components and investments.

For the cases of DH and DC market shares and infrastructure relevance could be analysed based on the performance of the operating NPP. A stronger connection between the amount of steam extracted and the required amount of heating needed could be investigate. A demand comparison of different locations and sizes of consumers could be implemented into the model and the economical profitability could be compared depending on the demand size. The modelling work in this thesis focuses on achieving a general estimation on how the performance and profitability of a NPP would be affected by implementing new energy utilities, real applications and demands could be investigated based on the work in this thesis. The assumption was made that there were no limitations on how large the demand could be for each utility. An interesting approach to future work would be to investigate how the limitations of infrastructure and transport would affect the performance and profitability of these implementations. One such aspect could be the storage possibilities for hydrogen if it was produced on-site. This thesis also focuses on the performance and economical evaluations of cogeneration where as future work could be done to investigate the impact of trigeneration.

There are also a lot of different approaches to the reference model. In the conducted work the focus was on a PWR. There are however modifications that could be made to the reference model depending on the type of NPP. These include but are not limited to BWR, gas cooled plants, molten salt reactors or lead cooled fast reactors, all operating under different conditions impacting available steam extractions. Another

approach would be to investigate how the capacity of the NPP affects the performance and profitability when implementing these energy utilities. A up and coming field in nuclear technology is the SMR where the electrical output may be a tenth of the capacity of a traditional large PWR. Future work could be done to analyse how the reduced amount of available steam could still supply a large secondary energy utility. By comparing steam utilization, potential performance improvements, and investment cost differences between a large PWR configuration and an SMR, insights can be gained to indicate which option might be more suitable for a future plant.

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# A

# Appendix: Reference model stream data

These stream data values are gathered from the simulation work done for the reference case. The streams are presented in figure E.1.

**Table A.1:** Stream Data for Reactor and Steam Cycle

| Stream | P (bar) | T (°C) | H (kJ/kg) | m (kg/s) | X |
|---|---|---|---|---|---|
| **Reactor** | | | | | |
| A | 155.00 | 323.00 | 1471.54 | 16213.10 | 0.00 |
| B | 155.00 | 323.00 | 1471.54 | 5350.32 | 0.00 |
| C | 153.65 | 322.91 | 1471.26 | 5350.32 | 0.00 |
| D | 153.65 | 290.19 | 1285.25 | 5350.32 | 0.00 |
| E | 152.30 | 286.76 | 1267.40 | 5350.32 | 0.00 |
| F | 152.30 | 286.76 | 1267.40 | 16213.10 | 0.00 |
| G | 155.00 | 286.87 | 1267.85 | 16213.10 | 0.00 |
| **Steam Cycle** | | | | | |
| 1 | 64.35 | 280.19 | 2779.60 | 571.68 | 1.00 |
| 2 | 63.00 | 279.00 | 2782.25 | 571.68 | 1.00 |
| 3 | 63.00 | 279.00 | 2782.25 | 1732.36 | 1.00 |
| 4 | 63.00 | 279.00 | 2782.25 | 866.18 | 1.00 |
| 5 | 47.50 | 260.76 | 2782.25 | 789.88 | 0.99 |
| 6 | 30.00 | 233.86 | 2707.19 | 701.35 | 0.95 |
| 7 | 10.00 | 179.89 | 2539.94 | 687.79 | 0.88 |
| 8 | 7.00 | 164.95 | 2488.94 | 687.79 | 0.87 |
| 9 | 7.00 | 164.95 | 2625.84 | 596.90 | 0.93 |
| 10 | 5.80 | 170.00 | 2784.44 | 596.90 | 1.00 |
| 11 | 4.60 | 260.00 | 2983.17 | 596.90 | 1.00 |
| 12 | 3.00 | 214.86 | 2896.40 | 562.13 | 1.00 |
| 13 | 1.00 | 115.43 | 2707.37 | 499.23 | 1.00 |
| 14 | 0.70 | 89.93 | 2654.00 | 499.23 | 1.00 |
| 15 | 0.04 | 28.96 | 2297.37 | 499.23 | 0.89 |

| **Stream** | **P (bar)** | **T (°C)** | **H (kJ/kg)** | **m (kg/s)** | **X** |
|---|---|---|---|---|---|
| 16 | 0.04 | 28.96 | 121.40 | 596.90 | 0.00 |
| 17 | 9.00 | 29.03 | 122.53 | 596.90 | 0.00 |
| 18 | 9.00 | 29.03 | 122.53 | 298.45 | 0.00 |
| 19 | 8.50 | 39.33 | 165.47 | 298.45 | 0.00 |
| 20 | 8.00 | 97.61 | 409.54 | 298.45 | 0.00 |
| 21 | 7.50 | 99.36 | 416.89 | 298.45 | 0.00 |
| 22 | 7.00 | 131.53 | 553.18 | 298.45 | 0.00 |
| 23 | 7.00 | 131.53 | 553.18 | 596.90 | 0.00 |
| 24 | 7.00 | 164.95 | 697.14 | 866.18 | 0.00 |
| 25 | 67.70 | 166.09 | 705.54 | 866.18 | 0.00 |
| 26 | 67.70 | 166.09 | 705.54 | 433.09 | 0.00 |
| 27 | 67.20 | 166.67 | 708.02 | 433.09 | 0.00 |
| 28 | 66.70 | 177.89 | 756.82 | 433.09 | 0.00 |
| 29 | 66.20 | 180.98 | 770.34 | 433.09 | 0.00 |
| 30 | 65.70 | 203.86 | 871.72 | 433.09 | 0.00 |
| 31 | 65.70 | 203.86 | 871.72 | 866.18 | 0.00 |
| 32 | 65.70 | 203.86 | 871.72 | 1732.36 | 0.00 |
| 33 | 65.70 | 203.86 | 871.72 | 571.68 | 0.00 |
| 34 | 64.35 | 240.19 | 1038.74 | 571.68 | 0.00 |

# B

# Appendix: Component parametrization

**Table B.1:** Component data and parametrization for components used in this thesis work

| **Component data** | **Value** | **Unit** |
|---|---|---|
| Evaporator Pinch Point Temperature | 10 | K |
| HP turbine efficiency $\eta_{turbine,is,HP}$ | 0.85 | - |
| LP turbine efficiency $\eta_{turbine,is,LP}$ | 0.88 | - |
| Condenser warming range | 10 | K |
| LP extraction FWH cold side pressure drop | 0.5 | bar |
| LP extraction FWH hot side pressure drop | 0.1 | bar |
| HP extraction FWH cold side pressure drop | 0.5 | bar |
| HP extraction FWH hot side pressure drop | 0.5 | bar |
| Electrolyser cell area | 360 | $cm^2$ |
| Number of cells per stack in electrolyser | 100 | - |

# C

# Appendix: Variables

**Table C.1:** Variables used throughout the thesis works techno-economic calculations

| **Description** | **Variable** | **Value** | **Unit** |
|---|---|---|---|
| % of DH demand winter | $\%_{DH_{winter}}$ | 70 | % |
| % of DH demand summer | $\%_{DH_{summer}}$ | 30 | % |
| % of electricity demand winter | $\%_{el_{winter}}$ | 0.7 | % |
| % of electricity demand summer | $\%_{el_{summer}}$ | 0.3 | % |
| Overall heat transfer coefficient | U | 2 | $W/m^2K$ |
| Cost of Heat Exchanger investment | $C_{area,HX}$ | 10 000 | $SEK/m^2$ |
| Cost per new installation | $C_{NewMatch,HX}$ | 3 000 000 | $SEK/unit$ |
| Number of new Heat Exchangers $DH$ | $N_n$ | 4 | - |
| Number of new Heat Exchangers $H_2$ | $N_n$ | 2 | - |
| Cost per new installation | $C_{NewMatch,Pump}$ | 500 000 | $SEK/unit$ |
| Number of new Pumps $DH$ | $N_n$ | 4 | - |
| Number of new Pumps $DC$ | $N_n$ | 0 | - |
| Number of new Pumps $H_2$ | $N_n$ | 2 | - |
| Interest rate | r | 0.05 | $yr^{-1}$ |
| Lifetime of components | l | 30 | yr |
| Annuity factor | AF | 0.065 | - |
| Exchange rate USD-SEK | (USD-SEK) | 1-10.06 | - |
| Exchange rate EUR-SEK | (EUR-SEK) | 1-11.00 | - |
| Price of electricity winter | $Price_{el,winter}$ | 54.46 | öre/kWh |
| Price of electricity summer | $Price_{el,summer}$ | 22.15 | öre/kWh |
| Price of heating utility winter | $Price_{DH,winter}$ | 20.00 | öre/kWh |
| Price of heating utility summer | $Price_{el,summer}$ | 10.00 | öre/kWh |
| Reference case electricity generation | $P_{el,reference}$ | 1130 | MW |
| Operational hours for the NPP | h | 8760 | Hours/year |
| % cost increase NEW PLANT | $\%_{increase_{NPP}}$ | 5 | % |
| % cost increase RETROFIT | $\%_{increase_{NPP}}$ | 100 | % |
| Operating hours NPP during winter | $h_{winter}$ | 4380 | - |
| Operating hours NPP during summer | $h_{summer}$ | 4380 | - |
| Cost per new installation | $C_{NewMatch,Absorber}$ | 5 000 000 | $SEK/unit$ |

**Table C.1:** Variables used throughout the thesis works techno-economic calculations

| **Description** | **Variable** | **Value** | **Unit** |
|---|---|---|---|
| Number of new absorbers | $N_n$ | 2 | - |
| Price of cold utility | $Price_{DC}$ | 23.87 | öre/kWh |
| Energy requirement input per kg of hydrogen produced | - | 40 | kWh/kg |
| Cost of electrolyser investment | $C_{Electrolyser}$ | 1200 | Euro/kW |
| Cost per new installation | $C_{NewMatch,Electrolyser}$ | 5 000 000 | $SEK/unit$ |
| Number of new Electrolysers | $N_n$ | 1 | - |
| Price of hydrogen utility | $Price_{H_2}$ | 80.84 | SEK/kg |

# D

# Appendix: Extra results

The following information and results are meant to complement the readers understanding of the project, while not adding or impacting the results or discussion.

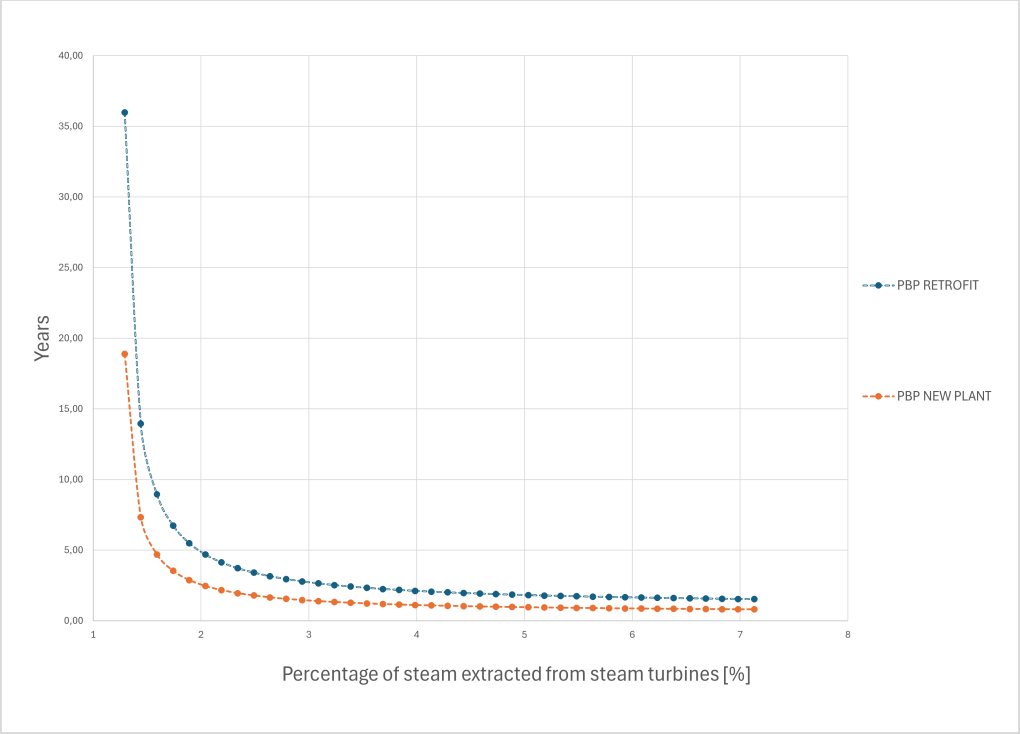


**Figure D.1:** Pay Back Period of implementing DH

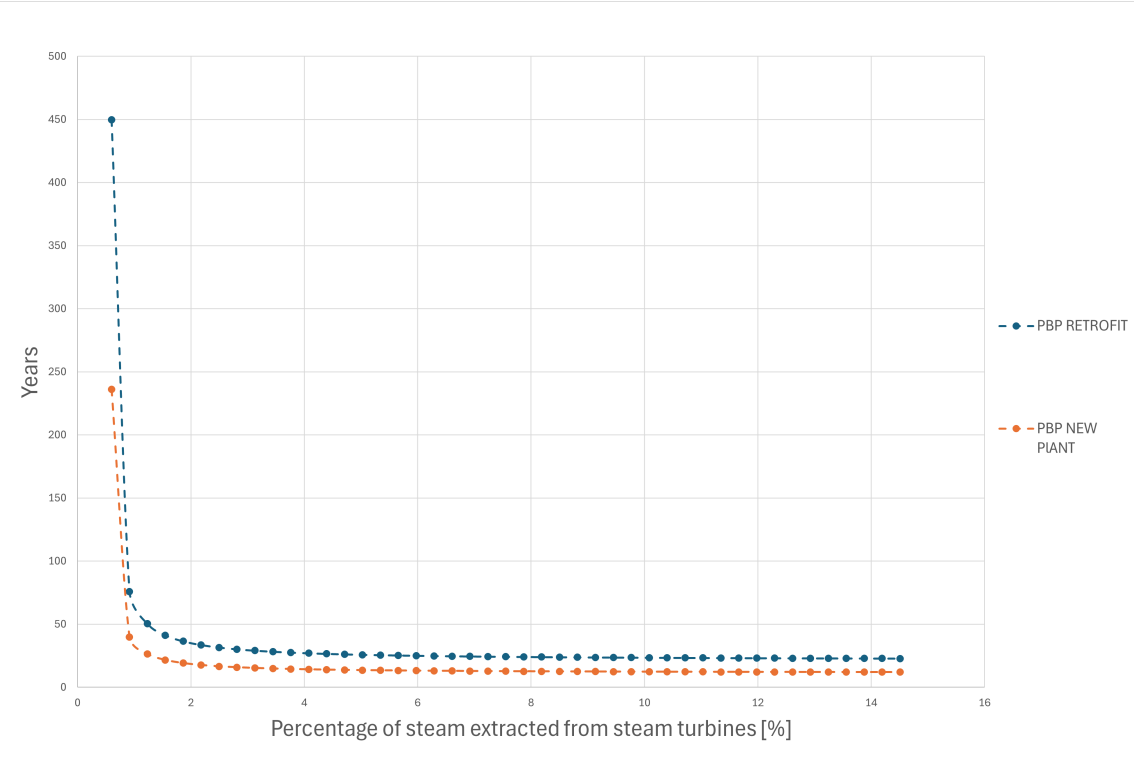


**Figure D.2:** Pay Back Period of implementing DC

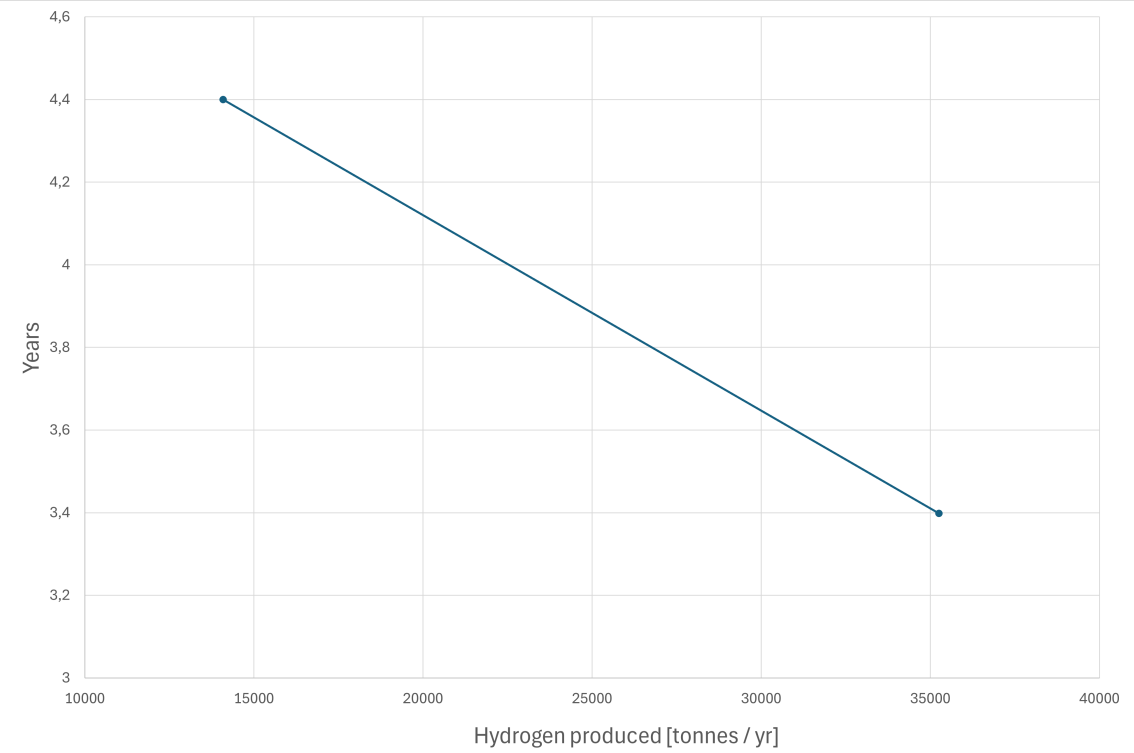


**Figure D.3:** Pay Back Period of implementing $H_2$

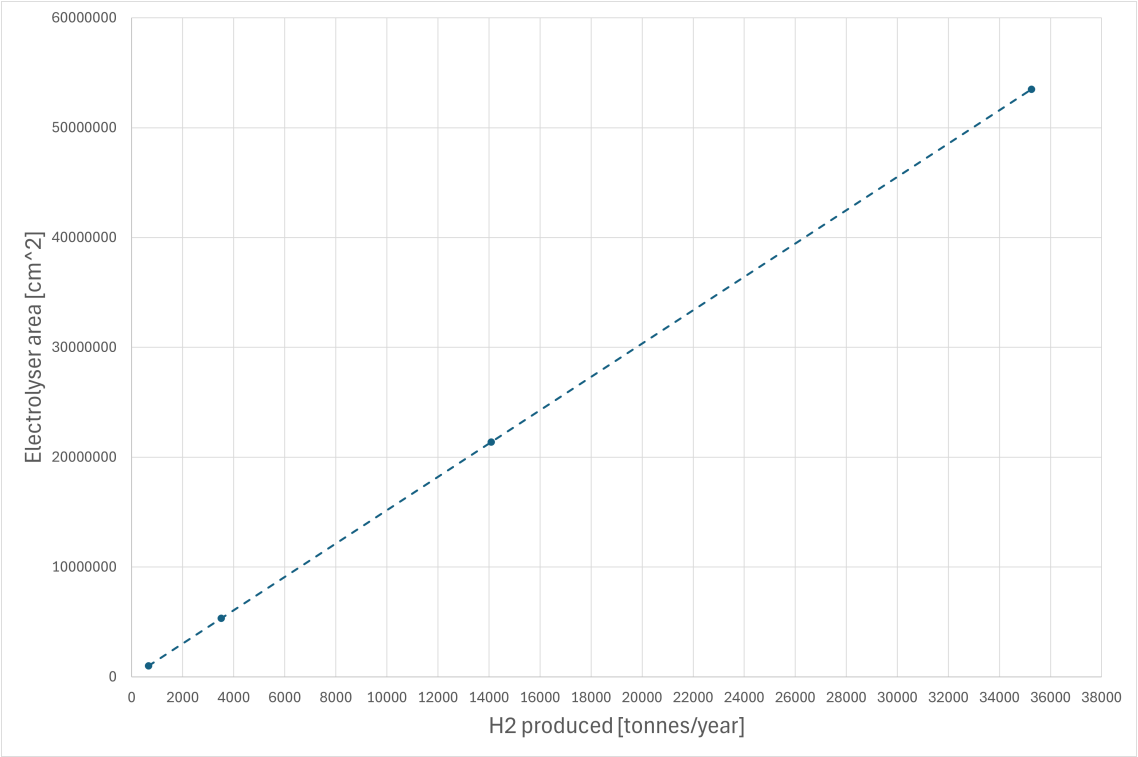


**Figure D.4:** Sizing of the electrolyser

# E

# Appendix: *Ebsilon Professional* Full Models

This Appendix presents the finalized models used for simulation and analysis for their respective energy utility cases.

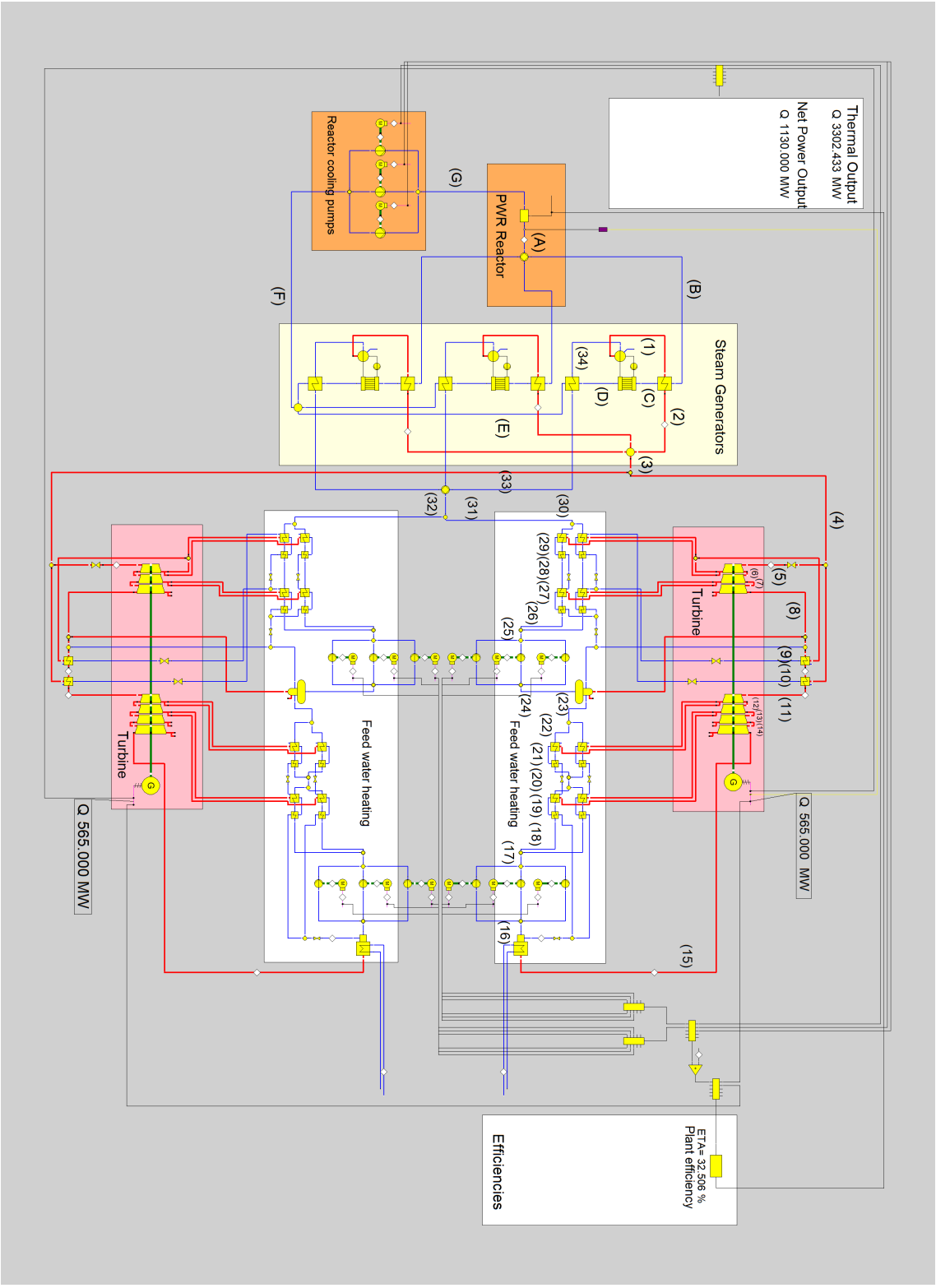


**Figure E.1:** Reference model, simulated in *Ebsilon Professional*

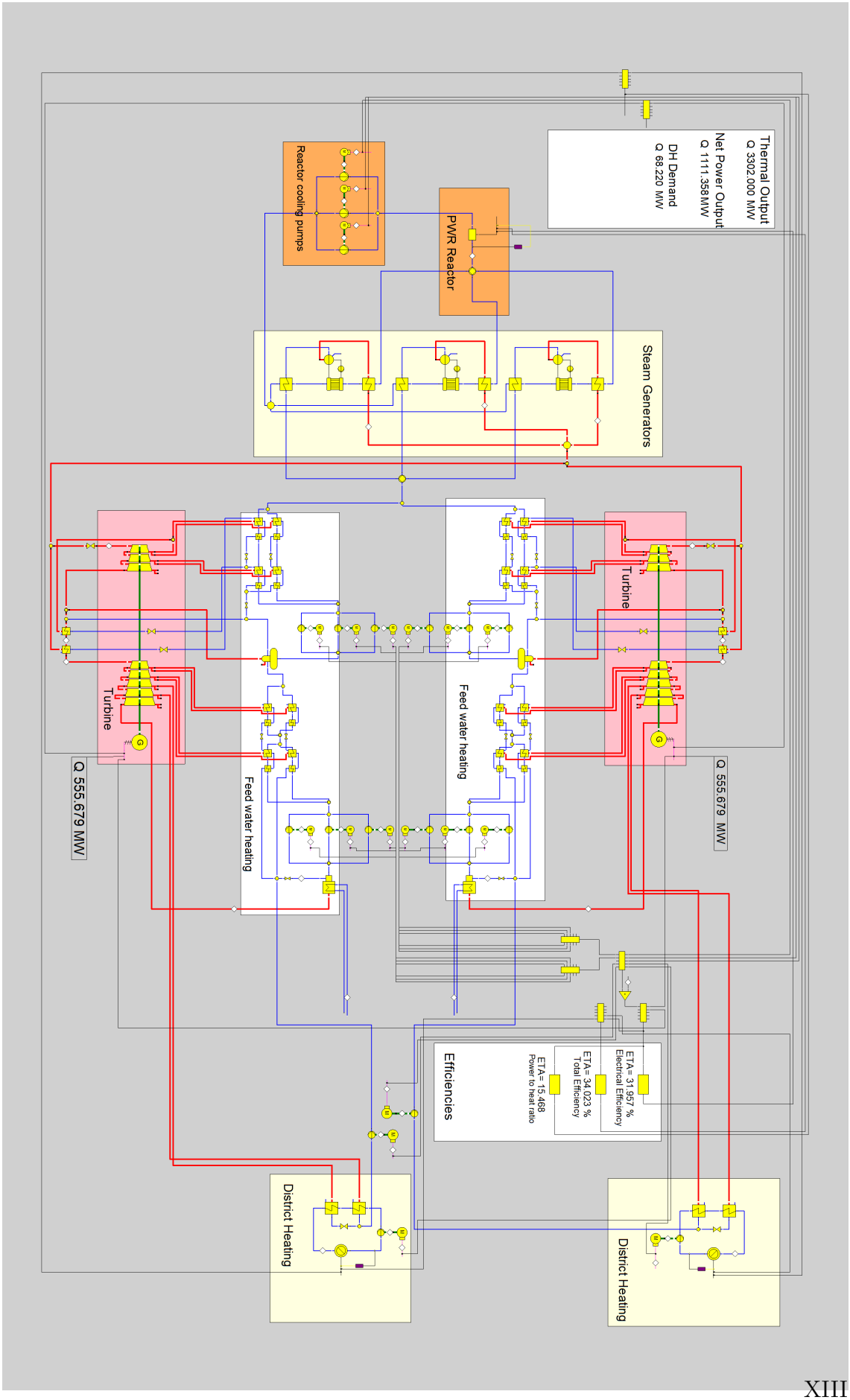




**Figure E.2:** DH model, simulated in *Ebsilon Professional*

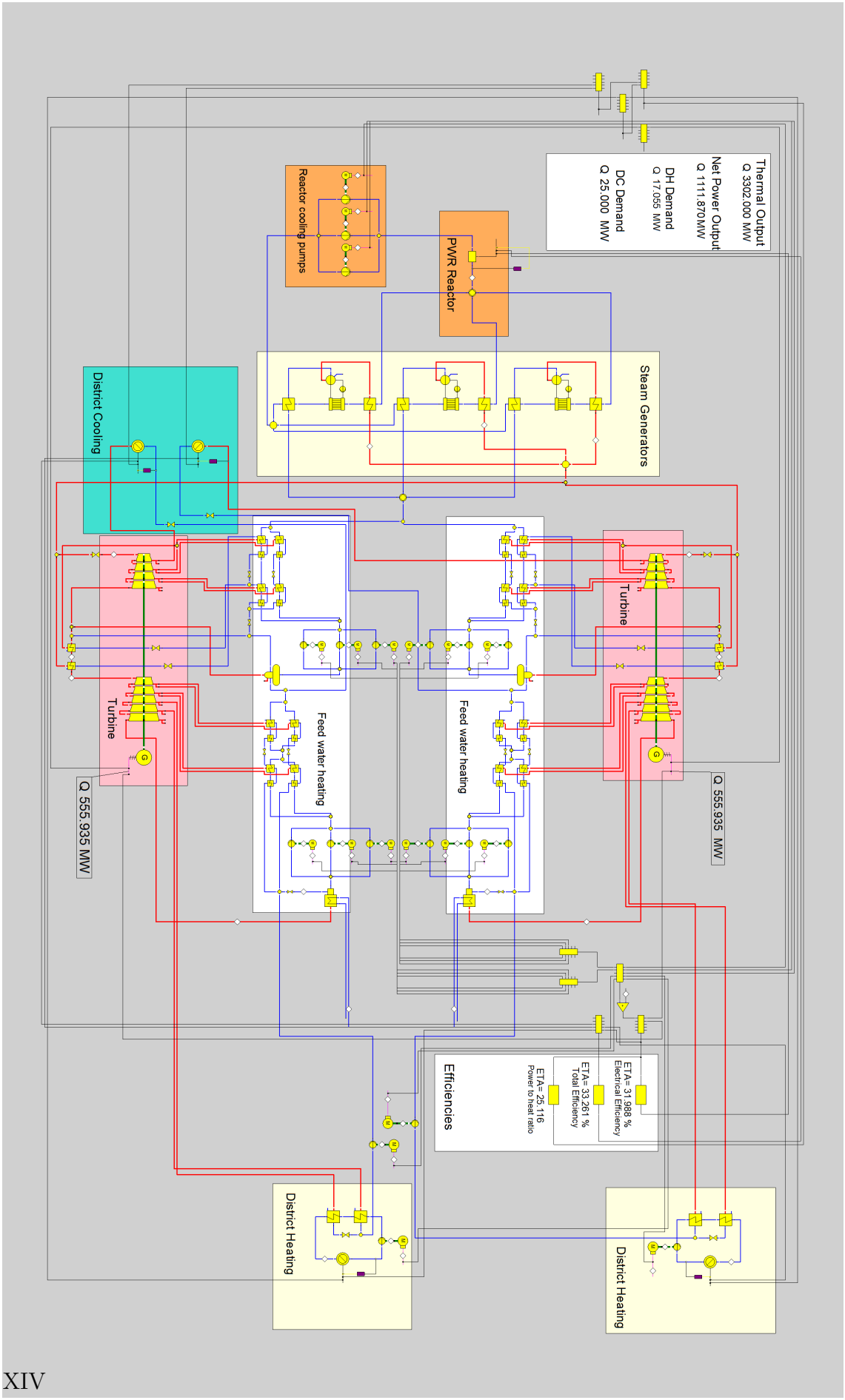




**Figure E.3:** DC model, simulated in *Ebsilon Professional*

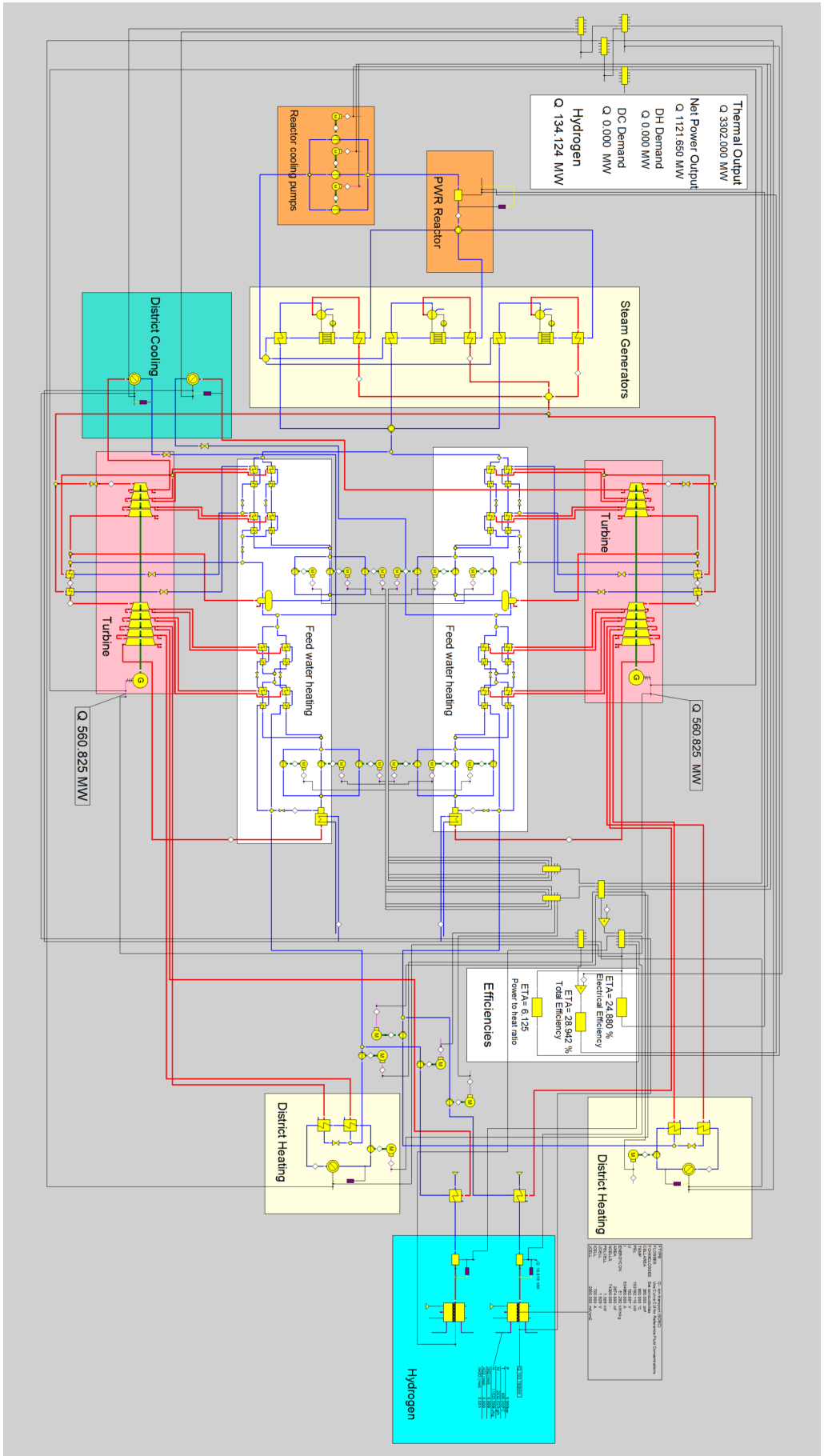


**Figure E.4:** Hydrogen model, simulated in *Ebsilon Professional*

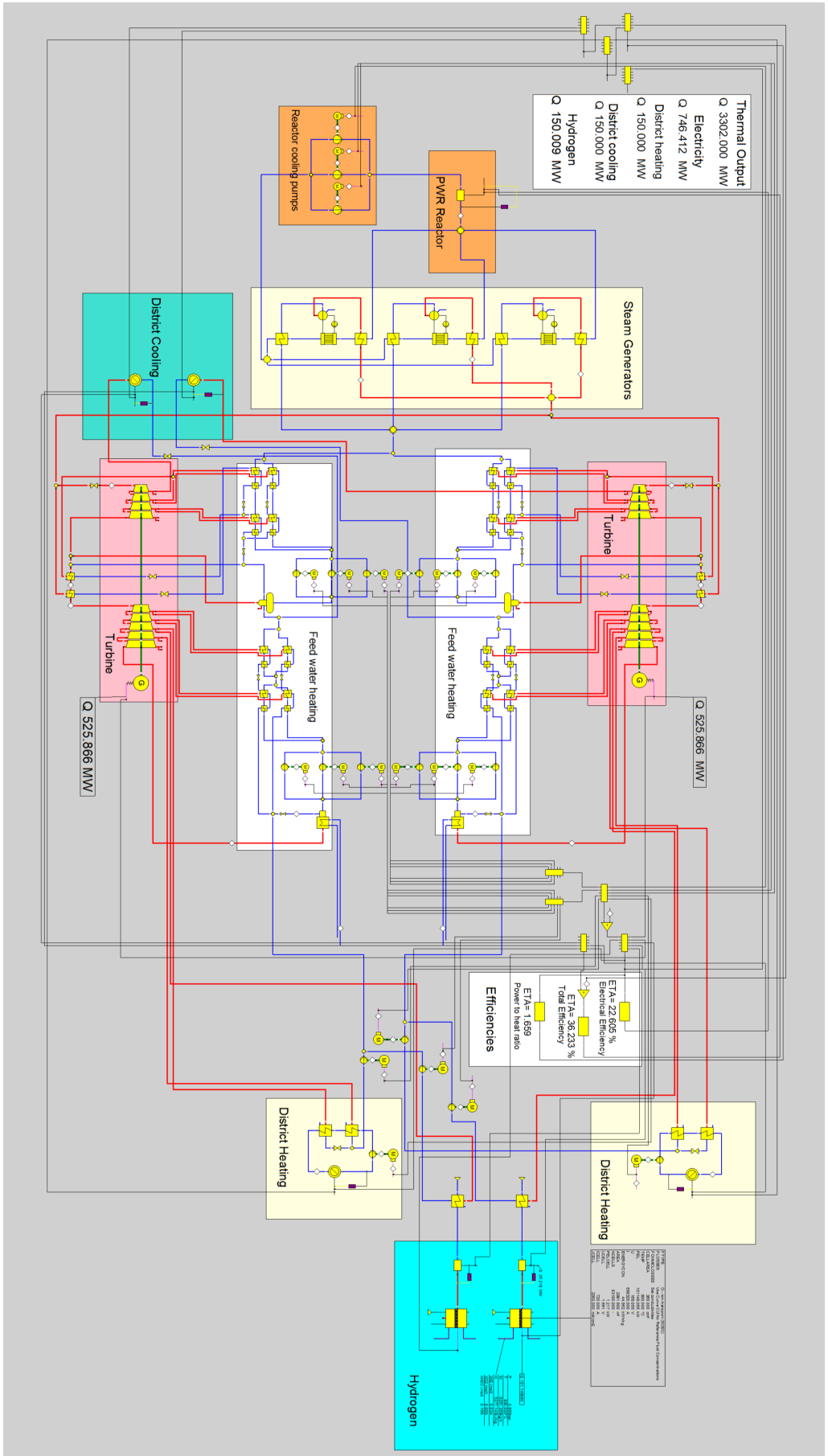


**Figure E.5:** Combined utility model, simulated in *Ebsilon Professional*

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