Hydrogen production and storage at Renova – A preliminary analysis

Master’s thesis in Sustainable Energy Systems

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DEPARTMENT OF PHYSICS
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2020
www.chalmers.se

CONTENT PAGES
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Cover:
The new hydrogen powered refuse collector/back loader that Renova has acquired (H. Zackrisson personal communication, June 1, 2020).

Chalmers, Göteborg, Sweden 2020

Abstract

Renova will test a fuel cell powered refuse collector/back loader truck in order to decrease emissions in the Gothenburg area. The truck requires compressed hydrogen as fuel and this report investigates the possibilities of refuelling the truck as well as producing and storing hydrogen for a single truck as well as for a future fleet growth in fuel cell trucks. The expected demand to refuel the hydrogen driven refuse collector/back loader is around 28 kilograms of hydrogen per day. At the start of the project, there were no hydrogen refuelling stations capable of refuelling at a pressure of 350 bar that were located within close proximity of Gothenburg. Due to the increase in interest from actors such as Renova, there are however plans to open two hydrogen stations within Gothenburg. There are various techniques that are used to produce hydrogen today, but those are primarily used in industry and the hydrogen originates from steam reforming of fossil fuels. In this project, the type of technology that is investigated to supply hydrogen is instead, electrolysis which requires, demineralised water and electricity input from the customer. Renova has multiple locations with buildings that could be used for solar cell installations which in turn could help supply the electricity needed for the hydrogen production. As the goal of Renova is to solve its refuelling issue a complete hydrogen refuelling station (HRS) has been investigated and companies that offer such a solution have been analysed. Among one of the operations that Renova has is a waste to energy (WTE) plant that due to lower demand of district heat (DH) during the summer, the plant needs to use cooling towers to cool the district heat to both meet the customer's demand but also allow for optimal operation. An opportunity is seen to try to utilise this low-grade heat and produce electricity that could be used to supply the electrolyser. The technology that is analysed to see if there is a possible connection point at the WTE plant is the so-called Organic Rankine Cycle (ORC). From the visits and analysis of the various locations that are owned and operated by Renova it can be seen that the potential electrical supply from solar cells being installed is greater than the calculated yearly demand of a typical HRS that would provide 28kg/day of hydrogen. Nevertheless, knowing that the interest from Renova has sparked an expansion of HRS in Gothenburg it would be advised to maybe wait and see how the hydrogen powered truck actually performs, if it meets the expected goals and in the meantime refuel from the HRS that is expected to become available in the summer of 2020. Due to the size and nature of the project, any major section from the energy recovery potential at the WTE plant, or rooftop solar cell installations or even the HRS itself is not seen as interlocking to the degree that an implementation would require every mentioned aspect to be met first. This means that the future work that would be needed could solely focus on each section. For example, for the solar cell installations the next advisable step would be to follow the solar cell guide from the Energy authority of Sweden. A possibility to better match the core goals of Renova and the hydrogen supply could be by investigating gasification of waste were both parts of the company, energy production and logistics could be involved.

Keywords: hydrogen, production, storage, ORC, Solar PV's, turn-key HRS.

Acknowledgements

The author wishes to thank his family for all the love and support. Additionally, the author wishes to thank his supervisor and examiner Bengt-Erik Mellander for all the support and guidance throughout the thesis project. A great big thank you is directed towards Renova ranging from Hans Zackrisson who also was a supervisor during the project who helped provide a lot of material that is used in the report. The author expresses his gratitude to Jonas Axner, the technical manager at Sävenäs, for valuable discussions on the opportunities to save or reuse energy at the Sävenäs plant. Thanks are also due to Malin Bruhn, who is a process engineer at Renova for explaining how the transfer of energy to the district heating network is vital for the proper operation of the plant and for explaining how the flue gas cleaning system benefits from this process. Additionally, thanks are also due to Camilla Svensson who is the facility coordinator, Daniel Rodhe who is in charge of the landfills at Renova for their insights and explanations of how Renova operates and uses among others its landfills. Additionally, gratitude's are due to Magnus Lundström who's position at Renova is to manage/refine Renova's properties but also change the properties operational needs that come. Magnus helped narrow down which buildings are more applicable for solar cell installation. The author is extremely grateful to Maria Grahn who is a Senior researcher at Chalmers University of Technology, at the department of Mechanics and Maritime Science, Maritime Environmental Science and who is also the Director of Energy Area of Advance for Chalmers University of Technology for her invaluable help in the discussion on the emissions from various fuels. The author is very thankful of the help received from Anna Derneryd who is a project manager at the regional energy agency of West Sweden who helped answer questions regarding solar cells. The author wishes to thank Dr. Jimmy Ehnberg who is a researcher at the division of Electric Power Engineering at the department of Electrical Engineering at Chalmers University of Technology for his help during the analysis of how the HRS could be supplied with electricity. Furthermore, thanks to the Againity AB team for the great hospitality at the study visit and the email correspondence were the authors questions were answered. The author would also like to thank Maurizio Furlani for the interesting discussions throughout the project. Many thanks to Liza Nordfeldt who is a librarian at the department of communication and learning science at Chalmers for her help in trying to accredit/reference the rightful owners of the information used in the report. Finally, many gratitude's are sent to the companies who were contacted and for their response/answers to the project.

Table of Contents

1 Introduction

The following report investigates the possibility of producing hydrogen to meet the refuelling needs for a fuel cell hydrogen driven truck. The report is done in collaboration with Renova.

1.1 Background

The Renova Group consists of two companies, the parent company Renova AB and the subsidiary Renova Miljö AB. Renova AB, carries out the assignments allocated directly by the owner municipalities. Renova Miljö AB operates in the competitive free market offering complete solutions in waste and recycling to businesses, municipalities and other public enterprises in its owners' region. Renova Group is owned by ten municipalities in western Sweden: Ale, Gothenburg, Härryda, Kungälv, Lerum, Mölndal, Partille, Stenungsund, Tjörn and Öckerö. The aim of Renova Group is to take responsibility of waste and recycling for the owner municipalities. As of 2019 the total number of employees were around 762, amount of treated waste was 1 153 400 tons, district heating produced was 1501 GWh and electricity produced was 279 GWh. Additionally, the number of heavy vehicles operated by Renova were around 280 in 2019 (Renova, 2019). The majority of heavy vehicles is found at Renova's' headquarters at Holmen in Gothenburg (Renova, n.d.). Out of the 280 vehicles around 100 of them are owned by Renova AB and the remainder is owned by Renova Miljö AB. To help the reader get a better understanding of the various locations that Renova has and operates figure 1 below is shown with the various locations marked and numbered.

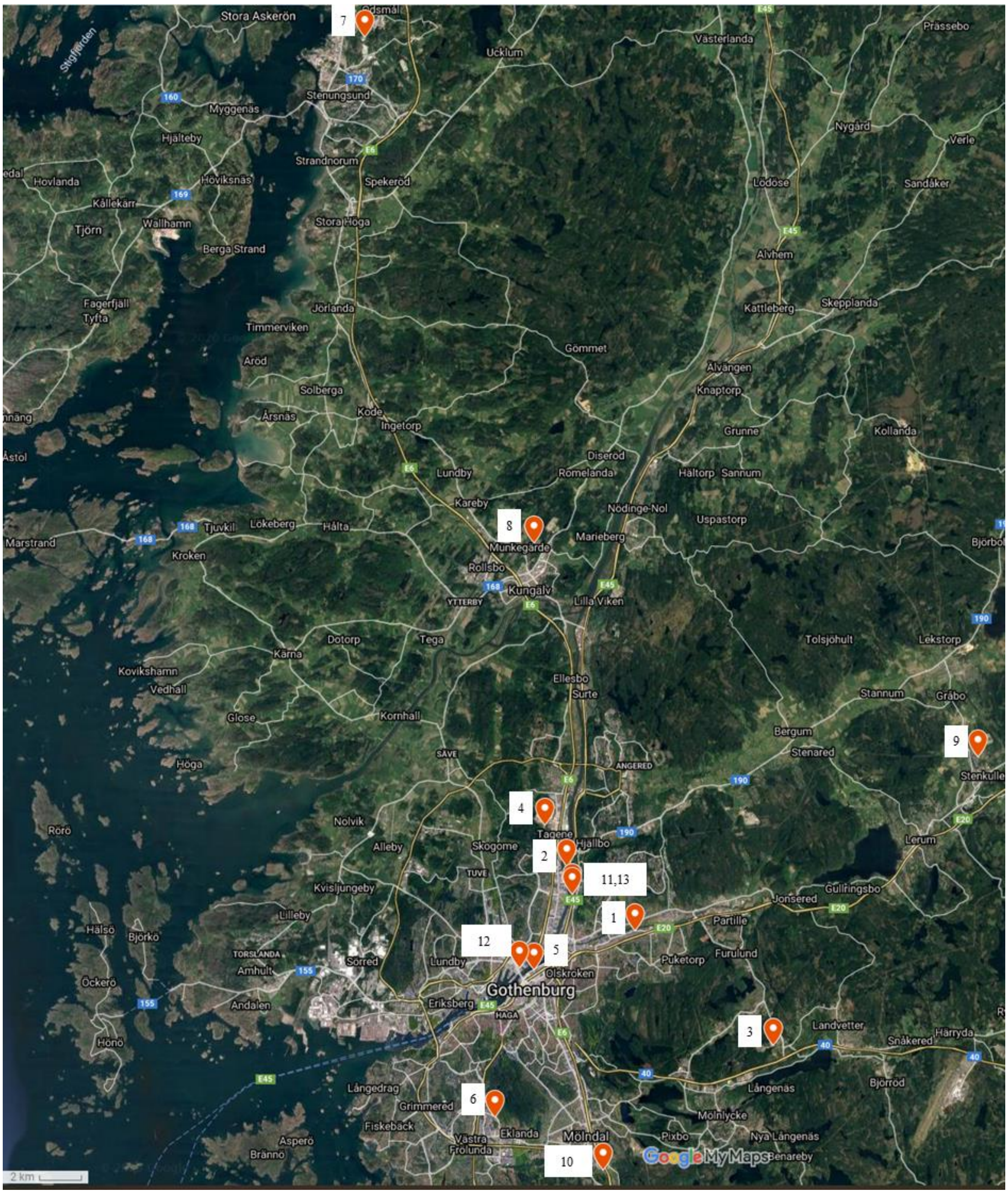


Figure 1: Various locations that Renova has and operates (Google Maps, n.d.).

Renova Group is spread out throughout its owners' municipalities but is primarily located in Gothenburg. This means that it has many premises with various functions serving Renova Group. A few key locations for Renova Group are its waste-to-energy plant located in eastern Gothenburg (referred to Renova Sävenäs) (no. 1 in figure 1), a treatment facility for sorted food waste which is located at Marieholm in Gothenburg (no. 2 in figure 1). Renova Group has two landfills (Fläskebo and Tagene (nos. 3 & 4 respectively in figure 1)) that are intended for contaminated soils, some hazardous waste and ashes from the waste-to-energy plant. As mentioned earlier the headquarters and most of the heavy vehicle fleet is found at Holmen in Gothenburg (no. 5 in figure 1). To save on unnecessary trips to Renova Sävenäs by the garbage trucks, transhipment stations are used were garbage trucks can empty and loaded trucks (around 30 ton) can transport the waste to Renova Sävenäs. The transhipment stations are found at Högsbo in Västra Frölunda, Kläpp in Stenungsund, Munkegärde in Kungälv, in Stenkullen and in Mölndal (nos. 6,7,8,9,10 respectively in figure 1). Furthermore, some of these transhipment stations also offer sorting services/facilities that sort unsorted-, combustible-, non-combustible- and construction-waste among others from companies. These sorting facilities are found in Högsbo in Västra Frölunda, Kläpp in Stenungsund, Munkegärde in Kungälv and Skräppekärr in Gothenburg (nos. 6,7,8,11 respectively in figure 1). Additionally, Renova Group has repair shops and an eco-friendly truck wash for their fleet, these are found in Gothenburg (nos. 12 & 5 respectively in figure 1). Additionally, at Marieholmsgatan Renova has a development centre called Rödingen. At Rödingen they test and develop future techniques for recycling and do practical tests in connection with new collection methods, for example corrugated cardboard is baled and plastic is sorted for further transport for recycling (no. 13 in figure 1)(Renova, n.d.).

Renova is actively trying to reduce the use of fossil fuels to drive their fleet of vehicles which in turn will reduce the company's carbon footprint. Renova is incrementally achieving this by firstly going from fossil diesel to Hydrogenated Vegetable Oil (HVO) diesel. The second step is by the electrification of the fleet. For example, an electric refuse truck that Renova, the city of Gothenburg and Volvo trucks have developed has been in use as of July 2019 (Renova, 2019). The third step that is identified in the heavy-duty field is the electrification through the use of hydrogen fuel cells (FC). Renova has ordered a fuel cell truck from Scania with a fuel cell system from Powercell, refuse equipment from JOAB and is in the processes of preparing it to be put in use.

At the beginning of the thesis project there were no active or planned hydrogen refuelling stations (HRS) in close proximity or within the Gothenburg region that Renova could use to refuel the hydrogen truck (H. Zackrisson personal communication, November 26, 2019). The closest active refuelling station was in Mariestad, with a refuelling pressure of 700 bar (Vätgas Sverige, n.d.). Unfortunately, the refuelling pressure of 700 bar is only suitable for passenger cars as the refuelling pressure of the truck follows the industry standard of 350 bar. Furthermore, the distance from Renova's headquarters to the refuelling station in Mariestad and back, would mean travelling over 320 km. The company thus has the issue of having the vehicles but no simple way of refuelling them and keeping them on the road. The aim of the thesis work is to try to identify and analyse the possibility of solving the refuelling issue by considering if Renova could have their own station to meet their demand. This entails gathering information from various aspects and actors both within the company and external actors that would help answer the question, how will the trucks be refuelled. Additionally, the Sävenäs waste-to-energy plant district heating (DH) supply during the summer period may exceed demand resulting in the need to cool the DH network via cooling towers. This means that useful thermal energy gets cooled to the atmosphere and not utilised. Part of the report will try to analyse the current situation of the Sävenäs plant and try identifying a possible solution to try and reduce the thermal energy loss.

It needs to be also stated that during the time that the thesis project has been worked on there has been growing interest from multiple actors to try and solve the refuelling issue. For example, the oil company OKQ8 is now planning to install a hydrogen refuelling station right next to Renova's headquarters, but the opening date is not fixed. By 2045 OKQ8 wants to become emission neutral in their whole chain of operations, and a hydrogen refuelling station is seen as helping reach their goal (Vätgas Sverige, 2020b). Additionally, there has been a refuelling station in Gothenburg, that could refuel with both 350 and 700 bars respectively, but it is out of commission for a while. It was bought from Woikoski by a company called Hynion Sweden and after some planned maintenance to the station it should be operational and open to the public around July-August 2020 (Vätgas Sverige, 2020a).

1.2 Type of trucks

As mentioned earlier Renova has approximately 280 vehicles, which they are distributed between Renova AB and Renova Miljö AB. Additionally, the company has multiple classes/types of vehicles that it uses for various purposes ranging from refuse collection trucks to garbage bin cleaning vehicles. To help give an overview and allocation of these 280 vehicles figure 2 below shows a bar graph for the amount and type of vehicles that Renova AB and Renova Miljö AB have.

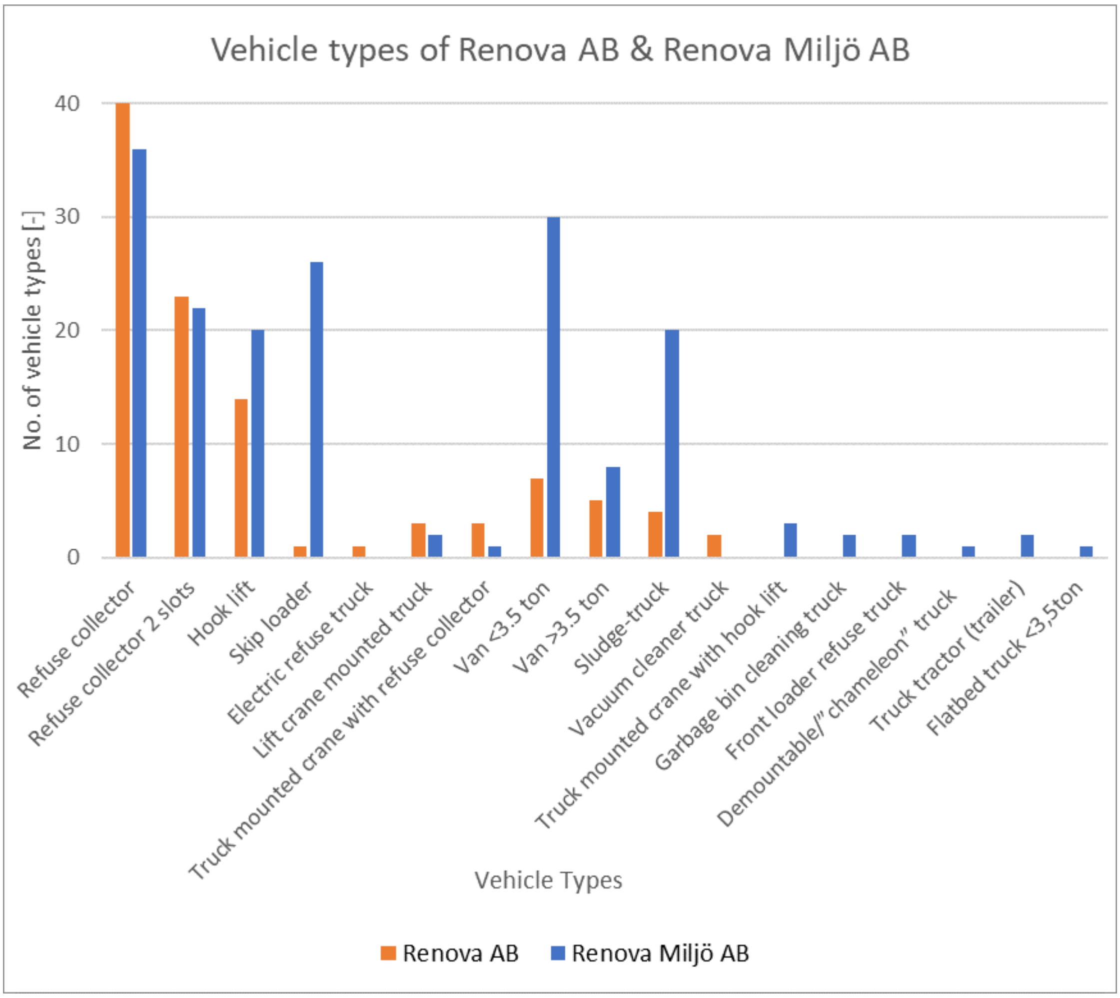


Figure 2: Vehicle types, amount, and allocation to Renova AB and Renova Miljö AB respectively. Source of values: (H. Zackrisson personal communication, March 4, 2020)

From figure 2, it can be seen that the largest amount of vehicles that is owned by both parties is the refuse collector/back loader (i.e. the typical truck that is used to collect household waste). The difference between the refuse collector and refuse collector with 2 slots is that the typical refuse collector can only carry one type of waste (e.g. household waste) while the 2 slots allows for a second kind of waste to be collected at the same time (e.g. one slot for waste and the other for food residues). In a way, both classes can be seen as having very similar type of vehicles, but the attachment is what varies between the two. Combining both types results in almost half of the total fleet being these kinds of vehicles. This is pointed out as the fuel cell driven truck that is expected to be put in use is also of the same kind (to be specific a refuse collection truck). In a way, having the fuel cell driven truck being of the same kind is good as it can represent the largest sector of the vehicle fleet of Renova. If this truck configuration works for the company, there is a large potential that the invested time could be spread to more vehicles (compared to only being a one-off vehicle) Furthermore, out of the 17 classes/types of vehicles, Renova Miljö AB has all types besides an electric refuse truck, or a vacuum cleaner truck. The case is such for the electric refuse truck as there is only one of them and it is more of a tester to see if such a vehicle would fit into the company way of work. A reason to why Renova Miljö AB has such a wide range of vehicle types is that as it operates in a free competitive market it needs to have multiple types of vehicles to be able to meet more customer demands. While Renova AB might not have as many types due to the fact that the vehicles serve the ten owner municipalities were a narrower kind of demand is needed. To help the reader get a better understanding of the various types of vehicles some figures are presented below which are seen as helpful whilst the remainder are shown in Appendix A. Figure 3 below shows the refuse collector where the refuse collector with 2 slots and the fuel cell driven truck could be assumed to look approximately the same.

Figure 3: Refuse collector truck side view, with a 2-slot refuse collector. The fuel cell driven truck can be assumed to look approximately the same (H. Zackrisson personal communication, April 27, 2020).

The vehicle from figure 3 can represent both types (refuse collector and refuse collector 2 slots), were vehicles that are smaller in dimension and weight are also classified in the same class. The refuse collector in figure 3 has an approximate length and width of 9.2 m and 2.55 m respectively. The total weight of the vehicle lies around 26 tons (H. Zackrisson personal communication, March 4, 2020). The average fuel consumption of the refuse collector is around 60 L/100km and the typical travelling distance is 1900 km/month (H. Zackrisson personal communication, March 4, 2020).

1.3 Fuel cell refuse collection truck

As mentioned earlier there are multiple actors involved in the fuel cell driven truck. Renova is the customer that is going to operate the vehicle, while Scania, PowerCell AB Sweden and JOAB are collaborating (including Renova) to build an electrified refuse truck along with an electrically driven compactor, where the electricity is supplied from fuel cells ("Scania fuel cell refuse truck developed with PowerCell, Renova," 2019). In short, the fuel cell driven truck is a refuse collection truck, with a maximum weight of 28 tons, it has six 200 L hydrogen storage tanks (used to carry hydrogen gas at 350 bar), the power of the fuel cell is around 100 kW, the battery that supplies the electricity has an energy storage of 56 kWh and the drivetrain connection can be assumed to mimic Battery Electric Vehicles (BEV) (H. Zackrisson personal communication, March 4, 2020).

What is meant when the drivetrain of the truck can be assumed to mimic that of a BEV is that there are a couple of different drivetrain designs that ultimately serve the same function of propelling the vehicle and powering the auxiliary components. The two main drivetrains are the series and parallel drivetrain connections, where the BEV is closer to the series drivetrain connection. Figure 4 below, illustrates a series and a parallel drivetrain configuration.

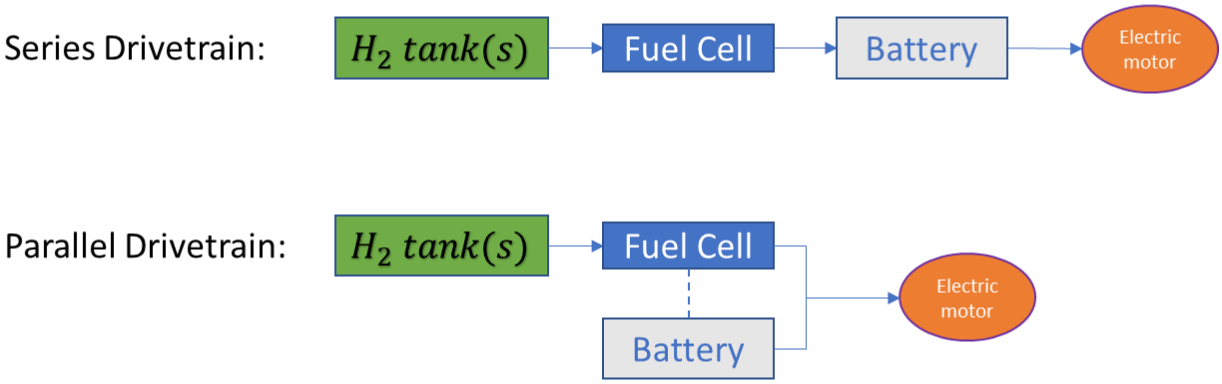


Figure 4: Series and Parallel drivetrain configurations, where the main difference is which mode can directly power the vehicle. Series allows only the battery to drive the motor, while parallel allows the fuel cell and the battery to drive the motor.

As seen in figure 4 the series drivetrain always powers the electric motor and auxiliary services through the battery and the fuel cell is used to top-up the battery and keep it charged. On the other hand, the parallel drivetrain allows both the fuel cell and the battery to power the electric motor; this is very similar to a hybrid vehicle that uses the battery for low speeds and an internal combustion engine for higher speeds. According to the fuel cell buses webpage, the advantages of a series connection drivetrain is that it is the best solution for stop-and-go city transportation (fuelcellbuses.eu, n.d.). Additionally, it is mentioned that the buses that have such a drivetrain are more efficient compared to buses that ran only on fuel cells (fuelcellbuses.eu, n.d.). The reference does mention about buses rather than refuse trucks, but they have more similarities than differences, they drive short distances between stops, they drive at low speeds, their auxiliary services consume quite a lot of power (cabin control for buses and compactor for truck) and they both work primarily in urban areas.

As the fuel cell size of the refuse collection truck is around 100 kW and is provided by PowerCell AB Sweden, looking at the homepage of the company, there are two variants of fuel cells with regard to sizes (power) and application area. The smaller of the two fuel cell stacks is called PowerCell S2 and has a power range of 3-35 kW (based on configuration and number of cells) (PowerCell Sweden AB, 2020). The PowerCell S3 fuel cell stack has a power range of 30-125 kW (PowerCell Sweden AB, 2020). Both types of fuel cells from PowerCell AB Sweden are based on the polymer electrolyte membrane or proton exchange membrane (PEM), the application areas vary from stationary to mobile and automotive applications (PowerCell Sweden AB, 2020). The power of the S3 fuel cell in the truck coincides with the power range of the S3 stack. Looking at the technical specifications of the S3 fuel cell stack, there is a fuel cell stack configuration that has a very similar power rating as the one in the truck (PowerCell Sweden AB, n.d.). The technical data about the fuel cell is shown in table 1 below.

Table 1: S3 (98kW) fuel cell standard stack data. Source of values: (PowerCell Sweden AB, n.d.)

Maximum Power [kW]	98
Number of PEM cells [-]	335
Dimensions [mm]	420×444×156
Weight [kg]	34
Fuel cell type	PEM

From table 1 it can be seen that quite a lot of cells are needed to be able to deliver the rated power (335 PEM cells deliver a maximum power of 98 kW). Additionally, the form factor for so many cells and power rating is quite small and the light weight make it a good choice for mobile applications, such as in a truck. Furthermore, according to the Office of energy efficiency & renewable energy at DOE, PEM fuel cells are predominantly used for mobile/transportation applications and as they work with low temperatures (compared to other types of fuel cells) they offer fast start-ups and good power-to-weight-ratios (Department of Energy, n.d.).

The expected range of the fuel cell driven refuse collection truck is around 260 km where around 50 km can be driven solely on the battery (H. Zackrisson personal communication, May 18, 2020). The expected payload for the refuse truck is around 10.5 tons; where the diesel, gas and electric variants can carry 12.1,10.7 and 8.5 tons respectively (H. Zackrisson personal communication, March 5, 2020). This in itself makes the fuel cell truck a good candidate for finding an alternative fuel for a vehicle that is clean (has no tail-pipe emissions) and can still carry a decent payload. The power of the drivetrain (both fuel cell and battery) is around 280 kW, the expected amount of hydrogen on board the vehicle is around 28 kg at 350 bar pressure and the weight of the fuel cell system is around 170 kg (H. Zackrisson personal communication, March 5, 2020).

The hydrogen storage tanks that are on the vehicle are from Agility fuel solutions whose mother company is Hexagon group (Agility Fuel Solutions, n.d.; Hexagon Group, n.d.). On the Hexagon group webpage, it is mentioned that they manufacture type 4 composite tanks both for 350 and 700 bar applications(Hexagon Group, n.d.). The reported capacity of the hydrogen storage is around 28.2 kg with the volume (referred as water volume) of 1200 L and a service pressure of 345 bar (Agility Fuel Solutions, n.d.).

Using the ideal gas equation,

$$PV = nRT \ (1)$$

where n represents the number of moles of a gas, R is the molar gas constant, T is the absolute temperature (in Kelvin), p is the pressure, V the volume and the values found on Agility Fuel Solutions webpage about the hydrogen tanks results in a hydrogen gas mass of 34.3 kg assuming a temperature of 20°C. This is approximately six kg more than the values stated by the manufacture (28.2 kg). However, some deviation is expected as in reality the ideal gas condition is not fulfilled but the deviation is seen as being too high regardless.

An email regarding this discrepancy was sent to the manufacturer by the author but there was no response, the proof to what the actual mass on board the truck will be seen when it is fuelled for the first time. However, a possibility could be that the regular operating maximum mass in the tanks could be 28.2 kg and for the initial fuelling 34.2 kg will be needed. This is suggested as it can be expected that there might be some residual hydrogen pressure left in the tanks even if the fuel meter shows empty. As there are six tanks and dividing the difference between the ideal gas law calculation and manufacturer values, results in approximately one kg of hydrogen per tank. In short after the initial fuelling there will always be some hydrogen left in the tanks and it can possibly be around six kg. This is mentioned as when the trucks are going to be serviced the hydrogen on board the truck will be released to allow for maintenance to be done in a safe environment/truck.

The expected demand for hydrogen will be around 14 kg per day initially and later on it is expected to double to, 28 kg per day (H. Zackrisson personal communication, March 13, 2020). With this in mind the demand that will be used in the remainder of the report will be 28 kg of hydrogen per day. The goal of Renova is that by 2030 they will own around 30 hydrogen fuelled trucks (H. Zackrisson personal communication, March 13, 2020).

1.4 General information about hydrogen

Hydrogen is the smallest element in the periodic table, at room temperature (around 20°C) it is a gas and at temperatures lower than -252.9°C it is a liquid. Additionally, hydrogen gas is odourless, has the lowest density of all gases, it is colourless and when pure hydrogen and oxygen burn the flame is clear (almost invisible to the naked eye) (Royal Society of Chemistry, 2020). This means that it is exceedingly difficult to detect without the help of sensors. A hydrogen to air gas mixture range of 4-75% is the explosive range for hydrogen while in comparison the corresponding methane to air mixture is around 5-15% (Carcassi & Fineschi, 2005). This in short means that hydrogen to air ratios smaller than 4% would not be an explosive risk as there is not enough fuel to combust. While ratios above 75% mean that there is too much fuel and too little air for combustion to be feasible but there is a greater risk of asphyxiation in confined areas that are mainly filled with hydrogen. From this it can be understood that a small hydrogen leakage in a badly ventilated environment can quickly become dangerous in the presence of heat or a spark. The temperature at which hydrogen would auto ignite (catch fire only because of heat) is around 500℃ (Patnaik, 2007). In the book "Photoelectrochemical hydrogen Production" which was edited by Roel van de Krol and Michael Grätzel a table was shown were some of the most common fuels were shown along with their energy content (by weight and volume) (van de Krol & Grätzel, 2012).The typical nomenclature for referring energy in terms of weight and volume is gravimetric and volumetric energy respectively. Table 2 below shows this table, were an addition was made were the energy content is also shown in kWh.

Table 2: Gravimetric and volumetric energy densities of most fuels at a pressure of 1 bar. The gravimetric in kWh column was created by dividing the gravimetric in MJ column by 3.6 (1 kWh = 3.6 MJ). Source of values: (van de Krol & Grätzel, 2012)

Fuel	Gravimetric in MJ [MJ/kg]	Volumetric [MJ/L]	Gravimetric in kWh [kWh/kg]
Coal	24	-	6.67
Wood	16	-	4.44
Gasoline (petrol)	44	35	12.22
Diesel	46	37	12.78
Methanol	20	18	5.56
Natural Gas	54	0.036	15.00
Hydrogen	143	0.011	39.72

To begin with, the gravimetric energy in table 2 is also shown in kWh due to the fact that most companies working within the hydrogen field, refer to these units (rather than MJ). Furthermore, the volumetric values for coal and wood are omitted as these fuels are typically in solid state and the volume can vary from species and types of fuels within the same class. From table 2 it can be understood why hydrogen is such a good candidate for an alternative fuel/energy carrier. This is mentioned as hydrogen's extremely large gravimetric energy density (almost 3 times that of natural gas) in combination with its low- greenhouse gas emissions (GHG's) from combustion with air (low since air has nitrogen in it and during combustion NO_x is formed) makes it a great choice. This combination is favourable in comparison to the other fuels that emit a lot more GHG's during combustion with air. The low amount of GHG's from hydrogen combustion could be mitigated all together by not combusting hydrogen gas with air, but instead being used in a fuel cell. However, due to hydrogens low volumetric energy density storage tanks capable of high pressures are needed for it to be applicable for mobile applications. Additionally, the values given for hydrogen in table 2 are the values for Higher Heating Value (HHV). While the lower heating value (LHV) of hydrogen is around 33.33 kWh/kg (Schlapbach & Züttel, 2001). The difference between HHV and LHV is that for the HHV the products (water) are brought back down to the reactant's temperature, while in the LHV the products (water) are left at a higher temperature and the energy calculated accordingly. In short, the HHV means that water vapour is condensed back to liquid while LHV keeps the water in vapour form. As changing phases (solid to liquid to gas) requires energy going in reverse results in energy being released and that is why the HHV is larger than the LHV. Table 3 below, summarises the key points that were discussed in the previous paragraphs.

Table 3: Summary table about hydrogen.

Lower expolsivity level (LEL) [%]	4
Upper explosivity level (UEL) [%]	75
Auto ignition [℃]	500
Energy density (HHV) [kWh/kg]	39.72
Energy density (LHV) [kWh/kg]	33.33

When it comes to the abundance of hydrogen on a universe basis, it is the most abundant element (where it can be found in the sun and most stars)(Royal Society of Chemistry, 2020). On Earth, the greatest quantities of hydrogen are found in water (Royal Society of Chemistry, 2020). Around 96.5% of all water on Earth is found in the oceans and surface wise around 71% of the earth is covered by water (usgs.gov, n.d.). In the atmosphere, hydrogen gas by volume is usually found in quantities less than 1 parts per million (ppm), while any unreacted hydrogen gas that escapes to the atmosphere is so light that it escapes the Earth's gravity and ends up in outer space (Royal Society of Chemistry, 2020).

Hydrogen has been used in many industries for a long time, for example, margarine involves using hydrogen to hydrogenate oils forming fats (which are used to make margarine) (Royal Society of Chemistry, 2020). Additionally, hydrogen is used in the oil-refining process where it is used to remove the sulphur from the oil (Royal Society of Chemistry, 2020). Furthermore, industries within steel making are also trying to reduce their carbon footprint by using hydrogen. For example, the Hybrit initiative between the steelmaker SSAB, electricity producer Vattenfall and iron ore specialist LKAB are trying to use hydrogen as the reductant [instead of coke] in the ore-based steel making (Houlton, 2019).

1.5 Fuel cell and electrolyser types

Fuel cells can be seen as having similarities with both combustion engines and batteries. When it comes to combustion engines the similarities between the two are that they both take in fuel (chemical energy stored in the fuel) from an external reservoir and convert it to mechanical power and ultimately electrical power. The difference between them is that the combustion engine needs the mechanical work first to produce electrical power while a fuel cell can skip that step (chemical energy directly converted to electrical energy). The similarities between batteries and fuel cells is that the output from both of them is electricity. The difference is that batteries store the chemical energy within the battery itself while fuel cells are like engines/factories that need an external supply of raw material/fuel to work. In terms of energy and power, the energy that a fuel cell system has is based on the capacity of hydrogen storage, while the power is directly correlated to the size of the fuel cell itself (O'Hayre et al., 2016). For example, the energy capacity of the fuel cell system on the hydrogen truck is related to the 28 kg of hydrogen stored on the truck and the power of the fuel cell is 100 kW. In a lecture given by Björn Wickman regarding fuel cells it was explained that the current that a fuel cell delivers depends on the total area of all the cells found in the fuel cell that are connected in parallel. The voltage from a fuel cell depends on the number of cells connected in series, multiplying the two (current and voltage) results in the expected/theoretical power from the fuel cell (B. Wickman personal communication, February 28, 2019). This is also seen in the Fuel Cells Fundamentals book by O'Hayre et.al where it mentions that connecting multiple single fuel cells in series allows the summation of their respective voltages (O'Hayre et al., 2016). This means that many individual fuel cells have to be connected both in parallel and in series to meet the demand, for example this is seen in table 1 were around 335 cells are needed to make up the 98 kW fuel cell unit. As with any system going from theory to reality always entails having some losses were fuel cells are no different. Some of the losses are due to resistive losses, activation losses (not all hydrogen molecules get broken down to allow electron movement), thermal losses and concentration losses (uneven distribution of hydrogen and oxygen across cell does not fully utilise the surface area of the fuel cell). Furthermore, a measure of comparing fuel cell performance is usually done by comparing the voltage output of a fuel cell at a given current load, this is usually seen in current-voltage curves (O'Hayre et al., 2016).

There are multiple types of fuel cells which have been developed and tested to varying degrees ranging from direct-liquid fuel cells that are driven by liquids (such as methanol) to biological fuel cells to the more developed PEM fuel cells. The reason that liquid fuel cells have not picked up yet is they tend to "exhibit poor power density and poor efficiency" (O'Hayre et al., 2016) compared to the hydrogen driven fuel cells making them less applicable for larger mobile application. Biological fuel cells are typically much smaller and use sugars such as glucose to enzymatically convert to electricity. In most fuel cell systems the way the electricity is generated can be summarised in four steps, the first being transporting the reactants to the fuel cell inner surfaces, followed by electrochemical reaction (breaking down the bonds e.g. hydrogen ions and electrons) thirdly the movement of the ions and electrons through the cell creating work, finally after the movement of the ions and the work being done the final products are formed and need to be removed to allow the fuel cell to continue to work. The product removal is necessary as by not removing the products would allow an equilibrium to be reached reducing the ability of more hydrogen being combined with oxygen creating electricity and water. For fuel cells the oxidation (liberation of electrons) occurs at the anode and reduction (consumption of electrons) at the cathode while for electrolysers this would occur at the opposite side (O'Hayre et al., 2016).

Out of the many types of fuel cells that have been developed and tested, the most promising types that offer the best possibilities for continued improvement are; the proton exchange membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC) (O'Hayre et al., 2016). Table 4 below shows the characteristics of the PEMFC and SOFC.

Table 4: PEMFC and SOFC characteristics. Source of values:(O'Hayre et al., 2016)

Fuel cell type [-]	PEMFC	SOFC
Electrolyte [-]	Polymer membrane	Ceramic
Charge carrier [-]	H^+	O^{2-}
Operating temperature [°C]	80	600-1000
Catalyst [-]	Platinum	Perovskites (ceramic)
Cell components [-]	Carbon based	Ceramic based
Fuel compatibility [-]	H_2, (methanol)	H_2, CH_4, CO
Electrical efficiency [%]	40-50	50-60
Power density [mW/cm²]	500-2500	250-500
Power range [kW]	0.001-1000	10-100 000
Internal reforming [-]	No	Yes
CO tolerance [%]	Poison (<50 ppm)	Fuel
Complexity of balance of plant [-]	Low-moderate	Moderate

Both types need an electrolyte to allow proper movement of the ions, where the PEMFC uses a polymer membrane and the SOFC uses a ceramic one. For PEMFC, the hydrogen ion is the so called charge carrier which means that it moves through the membrane to the other side to be reacted with the oxygen (also means that the electron is taken from the hydrogen molecule and forced to move through an external circuit to the other side of the cell). When it comes to the SOFC it is the oxygen molecule that moves across the electrolyte. The PEMFC is amongst the lowest operating temperature fuel cells while the SOFC is amongst the highest working temperature fuel cells. To aid in understanding what was stated earlier figure 5 below illustrates how a single PEM fuel cell operates along with the half-cell reactions.

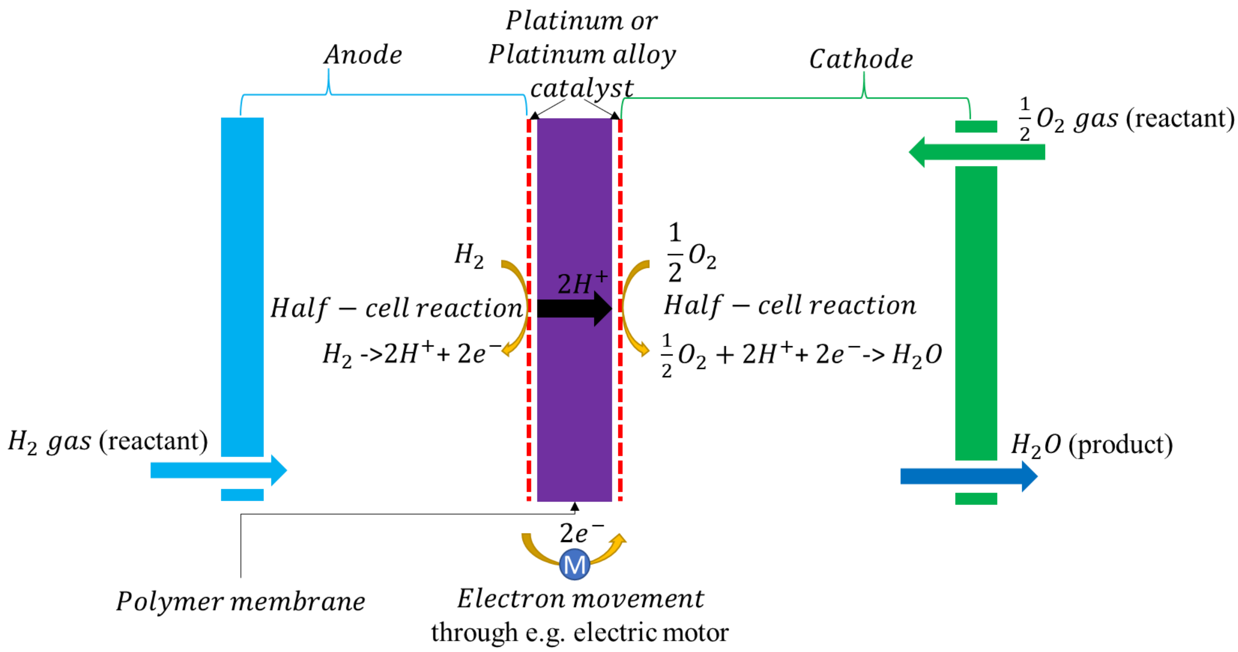


Figure 5: A graphical representation of a single PEM fuel cell. It should be added that the polymer membrane must be adequately hydrated with liquid water to maintain proper conductivity of hydrogen ions. Source: (O'Hayre et al., 2016)

In short, the lower the working temperature of a fuel cell the less tolerant it is to foreign particles (contaminants) in the fuel supply and vice versa. With this said, working at lower temperatures also means that precious metals (such as platinum for PEMFC) are needed to catalyse the hydrogen molecule to hydrogen ions and electrons as it cannot take advantage of elevated temperatures to break the molecule. As the SOFC operates at such high temperatures it can use less expensive, non-precious metal catalyst but thermally stable materials (such as Nickel (Ni) perovskites which are a form of ceramics) to produce electricity. Additionally, the cell anode and cathode are typically carbon based for PEMFC's and ceramic based for SOFC's as they are inert materials that do not affect the process and can withstand high levels of heat (in the case for the SOFC). When it comes to fuel compatibility the SOFC can work with larger variants of fuel quality as the cell works at much higher temperatures which allow it to reform (break down the molecules further) the molecules and compounds. As the SOFC can work with such a wide range of fuels it cannot be poisoned by carbon monoxide, instead it can used it as fuel to be oxidised with oxygen and produce carbon dioxide. The PEMFC is a lot more sensitive to the contents of the fuel, pure hydrogen is the ideal fuel composition for PEMFC (and for most fuel cells) and if there are traces of carbon monoxide in greater concentrations than 50 parts per million it would risk damaging the catalyst and affect the performance of the cell. The reasoning behind such a high sensitivity to just carbon monoxide is due to the fact that the platinum catalyst catalyses the carbon monoxide but the carbon remains adsorbed to the catalyst (the bond energy between the platinum and carbon is too strong) effectively reducing its surface area available for hydrogen catalysis. As the PEMFC is a low temperature fuel cell it does not have internal reforming. Furthermore, when it comes to the complexity of the balance of plant (i.e. everything around the fuel cell that is needed to ensure proper operation) is greatly affected by the fuel type. The simpler the fuel composition being inputted the simpler the handling of the products and the running process. Also, the temperature is an issue for the balance of plant as the operating temperatures of the fuel cells require cooling and/or heating for both the PEMFC and SOFC. Heating would be required to bring the cells to their operating temperatures while cooling would be needed to limit the amount of heat that is generated (O'Hayre et al., 2016).

The power density, operating temperatures, and good start-stop cycling tolerances/durability makes the PEMFC a perfect candidate for mobile applications. However, some disadvantages of PEMFC's are the expensive membranes, cell components and platinum catalyst while also having low CO tolerance and improper water management can make the cell underperform. The large power range, electrical efficiency, varied fuel supply capability and non-precious metal catalyst makes the SOFC a perfect candidate for stationary power applications. Additionally, as the SOFC works at such high temperatures this also makes it applicable for combined heat and power plants (CHP's) due to high quality residual heat from running such a fuel cell. Some disadvantages of the SOFC's are due to the high operating temperatures which include the system complexity, high temperature sealants (which is a major issue during thermal cycling) and quite expensive cell components and fabrication (O'Hayre et al., 2016).

Electrolysers can be seen as fuel cells run in reverse, where water and electricity are supplied, and hydrogen and oxygen are the products from the process. While in a fuel cell the opposite occurs, where hydrogen and oxygen are supplied and water and electricity (and some heat) are the products. The two most common type of electrolysers that can be bought today are alkaline electrolysis cells (AEC's) and proton exchange membrane electrolysis cells (PEMEC's) (Schmidt et al., 2017). Typically, they are referred to as alkaline and PEM electrolysers. As mentioned in the name alkaline electrolysers work in a basic environment, while PEM electrolysers work in an acidic environment.

Table 5: Main properties of AEC and PEMEC units. Source of values: (Schmidt et al., 2017)

Electrolyser type [-]	AEC	PEMEC
Electrolyte [-]	Aqueous potassium hydroxide around (20-40 wt% KOH)	Polymer membrane (e.g. Nafion)
Current density [A/cm²]	0.2-0.4	0.6-2.0
Operating temperature [°C]	60-80	50-80
Operating pressure [bar]	<30	<200
Hydrogen production rate [m³/h]	<760	<40
System energy [kWh_el/m³_H2]	4.5-6.6	4.2-6.6
Gas purity [%]	>99.5	99.99
Lowest operating range of maximum production [%]	10-40	0-10
System repsonse [-]	Seconds	Milliseconds
Cold-start time [min]	<60	<20
System maturity [-]	Mature	Commercial
Expected stack life [h]	60 000-90 000	20 000-60 000
Capital Cost [€/kW_el]	1000-1200	1860-2320

AEC electrolysers, are seen as a mature technology, as it has been used since the 1920's. The systems are readily available, have lower capital costs due to not using noble metals (compared to PEMEC), are durable (longer stack life than PEMEC), and due to the electrolyser type being in use for so long it has allowed relatively mature stack components (the longer something is in use the more time available for improvements on system design and components) (Schmidt et al., 2017). Unfortunately, hydrogen production costs and system size are negatively affected due to the low current density (in a way requiring more units/components to produce the same amount compared to other types) and low operating pressure (Schmidt et al., 2017). Furthermore, the operation of the AEC electrolyser type (varying power input and often/frequent start-ups) is restricted as it can affect the system efficiency and gas purity negatively (ideal choice would be to have a stable continuous production to keep a good efficiency and quality of gas) (Schmidt et al., 2017). As this is the case for this type of electrolyser, to make it more applicable for intermittent power generation (such as wind, solar etc.) for example, more research is being conducted to improve the systems capability of working with more varied input and frequent start-ups, increasing current density and operating pressure to bring down the size of the units (Schmidt et al., 2017). Furthermore, it is suggested that one of the biggest drivers to cost reductions are likely due to economies of scale allowing to bring prices down for each unit produced (Schmidt et al., 2017). From multiple parameters from table 5 (low current density, long start up time, large production capacity, lower capital cost (compared to PEMEC)) alkaline electrolysers are best suited for large central hydrogen production stations. Both electrolyser types work at relatively low temperatures from 50-80°C.

PEMEC electrolysers have their origins from the "solid polymer electrolyte (SPE) concept for water electrolysis that was first introduced in the 1960s" (Schmidt et al., 2017). This type of electrolyser system was developed by General Electric to try to overcome the issues/drawbacks of the AEC electrolysers (e.g. low current densities, cold start time etc.) (Schmidt et al., 2017). In comparison to the AEC's, PEMEC's are seen as being a less mature technology (due to being less years in the electrolyser market) in comparison to AEC's and is mostly directed to small-scale purposes (due to capital costs, and low production rates), such as laboratories (Schmidt et al., 2017). Despite the less mature technology PEMEC's have a high-power density, high efficiency, flexible operation (frequent start-ups and varying electrical input), high purity and pressurised hydrogen gas allowing for smaller unit sizes (Schmidt et al., 2017). Such benefits do come with some drawbacks some of them being that they are more expensive due to the platinum catalysts needed, the membrane materials have fluorine in them, shorter lifetime than the AEC electrolyser type, high water purity requirements and a complex system due to the higher working pressures (Schmidt et al., 2017). To make the PEMEC electrolysers more attractive, current improvement/research areas include reduction in system complexity to allow for easier manufacturing up-scale (economies of scale), cheaper alternative raw materials and "more sophisticated stack manufacturing processes" (Schmidt et al., 2017) probably through more automation rather than manual labour (Schmidt et al., 2017).

1.6 Hydrogen production

A report from The Royal Society, which tries to bridge the gap of science with policy makers outlines four various methods of producing hydrogen. The first type of hydrogen production involves heat and fossil fuels and is referred to as thermochemical route to hydrogen, where steam methane reforming is the most dominant commercial technology and supplier of hydrogen. Steam methane reforming of natural gas and coal gasification account roughly 95% of the global production of hydrogen (primarily by steam reforming). Steam methane reforming involves steam and natural gas mixed at high temperatures over a catalyst that results in carbon monoxide and hydrogen gas (usually referred to as syngas). Other types of thermochemical routes that can be used are coal gasification, biomass gasification and pyrolysis of hydrocarbons among others. All these processes have the common denominator of having a raw material rich in hydrocarbons, or rich in carbon where through the addition of heat usually in the absence of oxygen results in bond breaking of these compounds where a mixture of products containing hydrogen can be collected. The difference between them are the level of pre-treatment needed where a known homogeneous product such as coal would need less pre-treatment compared to biomass and the maturity of technology, where for example the technology for pyrolysis of hydrocarbons is seen as being in very early stages of research. Unfortunately, as all these technologies rely on carbon-based feedstocks means that carbon dioxide is emitted to extract the hydrogen. Without the implementation of carbon capture and storage (CCS) would mean that hydrogen production would still be negatively affecting the global warming problem (The Royal Society, 2018).

In an article from the International Energy Agency, Mr. van Hulst, who is part of the hydrogen envoy at the Ministry of economic affairs & climate policy of the Netherlands, mentions three types of hydrogen. The methane reformed hydrogen without any CCS is called "grey " hydrogen, while reformed hydrogen with CCS installations is called "blue" hydrogen and finally "green" hydrogen which involves no carbon emissions to begin with as renewable resources are used to produce electricity to drive an electrolyser. In the article from the IEA it is mentioned that the cheapest hydrogen at the moment is the so called "grey" hydrogen at a price of 1.50 €/kg of hydrogen. This would not be the case if more subsidies were provided to incentivise "blue" or "green" hydrogen production by for example increasing the carbon dioxide emissions tax. At the moment based on various factors the price of "green hydrogen" is estimated to be around 3.50-5 €/kg of hydrogen. Some factors that affect the price is the cost of electricity from renewables and the cost for electrolyser units. In the IEA article it mentions that most industry experts, expect the costs of electrolysis units to be reduced by around 70% in the next 10 years (IEA, 2019).

The second method for producing hydrogen that is mentioned in the Royal Society report, is the electrolytic routes. In short, this route involves using electricity to split water to hydrogen and oxygen via electrolysers. The most common electrolysers (alkaline and PEM) where mentioned and analysed in the previous section.

A third type which is mentioned in the report is the solid oxide electrolysers which have the least mature technology compared to PEM and alkaline electrolysers, but could offer the highest efficiencies out of the three types as long as it could be coupled to a suitable heat source. The improvement areas that are needed from these types of electrolysers are, longer life span, lower capital costs, high hydrogen production rates and efficiencies, smaller size factor/footprint and grid balancing for intermittent renewable generation (The Royal Society, 2018).

In the hydrogen storage methods paper from A. Züttel it is mentioned that at ambient pressure and temperature the minimum energy needed to produce one kilogram of hydrogen would roughly be 39.7 kWh. Electrolysers are found to have an electrical efficiency of 85% and require 47 kWh/kg hydrogen (Züttel, 2004).

In the report from the Royal Society, the first two methods of producing hydrogen are seen as the main technologies that will provide hydrogen for the near to mid-term future. Therefore, the other two methods might be seen as more of a niche solution and will be named and described shortly/briefly. The remaining two routes to produce hydrogen are the biological and solar to fuels route. In short, the biological route involves using anaerobic digestion of organic materials to directly produce hydrogen (rather than biogas). This technology may be best suited to produce chemicals for biorefineries and is now at a laboratory to small pilot plant scales (The Royal Society, 2018). The solar to fuels route, involves using sunlight to split water directly to oxygen and hydrogen. Some call the last route the holy grail as allowing to produce hydrogen directly from sunlight would require less steps to producing hydrogen, requiring less raw materials (solar PV's, electrolysers etc.) and the "infinite" abundance of sunlight is seen as the best source of "green" energy. This however is still in development and would always mean that there would be competition for land, potentially limiting the scaling up of this production method (The Royal Society, 2018).

To round-off the hydrogen production techniques, table 6 and figure 6 below, provide an example of the typical composition of biogas from a biogas digester of household organic waste and the clean-up required to clean the biogas to various levels for various types of fuel cells respectively.

Table 6: Typical composition of biogas from household organic waste. Source of values: (Hoogers, 2003)

Chemical components [-]	Concentration of wet gas [-]
Methane (CH_4)	60-75 [%]
Carbon dioxide (CO_2)	<35 [%]
Water vapour (H_2O)	0-10 [%]
Nitrogen (N_2)	<5 [%]
Oxygen (O_2)	<1 [%]
Carbon monoxide (CO)	0.2 [%]
Siloxanes (silicone compounds)	<10 [mg/m^3 of CH_4]
Hydrogen sulphide (H_2S)	150 [ppm]

From table 6 it can be seen that most chemical components (both compound and molecules) are derived due to the breakdown of organic matter in digesters which usually work in the absence of air. The only compounds that are seen as not being directly derived from the digestion process of breaking down of organic matter are siloxanes. Siloxanes are commonly used in both industrial and commercial applications/products, due to the compounds ability to resist water (hydrophobicity), high flexibility and low thermal conductivity (Siloxane - an overview, n.d.). Examples of products include, cosmetics, household-, electronic -products and in medical devices (Siloxane - an overview, n.d.).

Figure 6 below, illustrates the clean-up procedure for biogas which is intended to be used in various types of fuel cells.

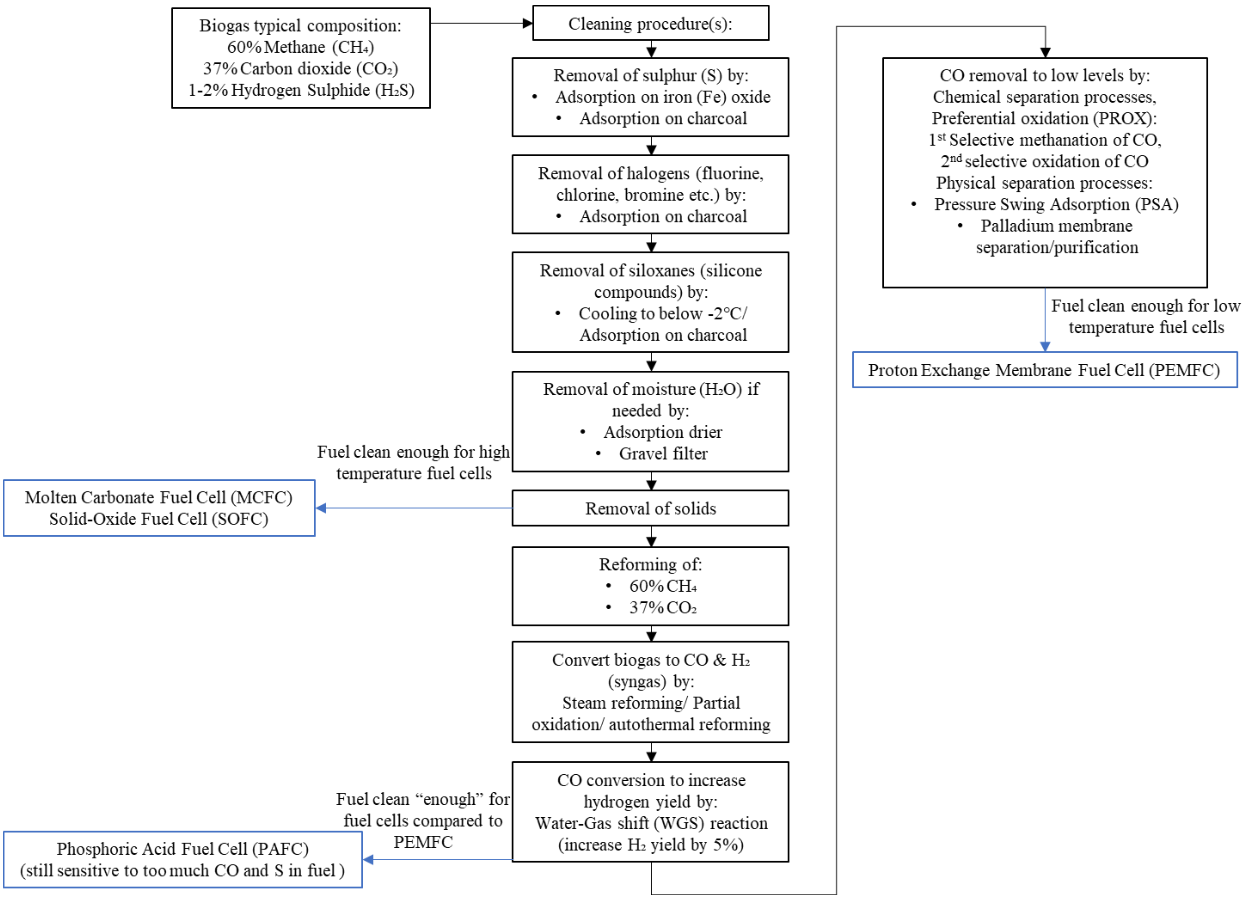


Figure 6: Clean-up procedure of biogas (black boxes) and which type of fuel cells can work with the fuel at various fuel cleanliness levels (blue boxes). Source of values: (Hoogers, 2003; O'Hayre et al., 2016)

Overall, due to the vast amounts of various chemical components in biogas, a long list of cleaning procedures where the biogas is gradually cleaned, and ultimately pure hydrogen is extracted. After the removal of solids, the clean-up procedure for biogas is the same as for reformed natural gas (natural gas mixed with steam results in syngas). The main reasoning to having figure 6 is to give the reader an overview of the clean-up process itself but also to get a feeling of the sensitivity between the fuel cell types (especially between the high temperature fuel cells and the low temperature). Due to the high operation temperature of fuel cells they can tolerate a great deal of "foreign" gases and particles rather than low temperature fuel cells such as PEMFC's that ultimately work best with pure hydrogen.

1.7 Hydrogen storage

In the review for hydrogen storage methods by Andreas Züttel six methods for storing hydrogen are listed. The first method involves compressing the hydrogen gas in high-pressure cylinders/canisters which are made of various materials with certain combinations allowing pressurising the gas up to 800 bars (Züttel, 2004). The second method involves cooling the hydrogen gas to temperatures below 21 K (-252°C) were it condenses to a liquid (referred to as cryogenic storage) but it can only be stored in open systems (Züttel, 2004). This is the case because in a sealed container at room temperature the pressure could increase to dangerous levels (around 10^4 bar) (Züttel, 2004). The third and fourth methods are storing the hydrogen on materials with large surface areas (adsorbed) at temperatures lower than 100 K, and being absorbed on interstitial sites (in simple terms the gaps between the molecules) of metals at ambient/room temperature and pressure (Züttel, 2004). The fourth storage method is usually referred to as metal hydrides and complex hydrides, were dense usually pure metals or alloys (usually light metals from group 1-3 from the periodic table) have a large surface area that allows the capturing of hydrogen with little to no extra effort (Züttel, 2004). However, some energy must be inputted to be able to release the hydrogen from such containers, usually by heating them. Furthermore, the fifth method to store hydrogen is through chemical bonds "in covalent and ionic compounds (at ambient pressure)" (Züttel, 2004). Finally, the sixth method for storing hydrogen would be by having metals that coming into contact with water would cause them to oxidise and release hydrogen (Züttel, 2004).

In liquid state the volumetric density of hydrogen is around 70.8 kg/m^3, while in compressed form at around 800 bar it is around 36 kg/m^3 (Züttel, 2004). In the review by Andreas Züttel an example was given were to store 4 kg of hydrogen in a metal hydride would result in an object weighing 300 kg with an approximate volume of 60 L (Züttel, 2004). This for the time being would be too heavy to have on board of a vehicle, but Züttel explains that with the best materials known today a storage density of 150 kg/m^3 is possible which could be theoretically improved by another 50% (Züttel, 2004). This is mentioned because if this were to become a reality it would make storing hydrogen safer, easier and with a smaller footprint. The fact that there is a possibility of storing something with a greater concentration when paired with other materials than in its liquid state might be counter intuitive, it is also stated in the Fuel Cell Fundamentals book by O'Hayre et al. where it states that "hydrogen gas atoms can be packed inside some metal hydrides in a manner that achieves a higher volumetric energy density than liquid hydrogen!" (O'Hayre et al., 2016). However, it is mentioned that the hydride materials are expensive, quite heavy which negatively affects cost and gravimetric energy density (O'Hayre et al., 2016). The most common type of high-pressure gas cylinders/canisters operate at a pressure of 200 bar, while canisters that can withstand 800 bars of pressure are made of composite materials (Züttel, 2004). As the most common type of storing hydrogen is by compressing and storing in canisters, the remainder of this section will be dedicated to describing the various types of canisters for compressed hydrogen gas. This is both useful in giving an insight into the composite canister that is found on the truck but also the most probable storage method for a refuelling station as well.

In the book Fuel Cell Fundamentals by O'Hayre et al. it states that "approximately 10% of the energy content of H_2 gas must be expended to pressurize it to 300 bars" (O'Hayre et al., 2016). Luckily as more hydrogen is found in the same volume at larger pressures the energy losses needed to compress the hydrogen do not follow a linear projection of pressure and energy needed (O'Hayre et al., 2016). There are 5 types of canisters that are used to contain compressed hydrogen. In ascending order, the types of storage containers go from single materials (usually metals) to more complex composites. This usually results in more carrying capacity containers, at a relatively lighter weight ratio (%wt.), at higher pressures, but unfortunately at higher costs (Barthélémy, n.d.). Type I hydrogen storage canisters are usually metal tanks with working pressures up to 200 bar, which are mostly used for stationary storage (Pohl & Ridell, n.d.). Type II storage tanks also use metal tanks (aluminium or steel) but are also wrapped/reinforced with carbon fibre composites (Pohl & Ridell, n.d.). Type III storage tanks are carbon fibre tanks that use a metal liner (usually aluminium) allowing storage pressures up to 350 bar (Pohl & Ridell, n.d.). Type IV storage tanks use composite reinforced tanks with a polymer inner liner that allow storage pressures up to 700 bar (Pohl & Ridell, n.d.). For example, the Toyota Mirai which is a fuel cell driven car has a two-tank storage system of Type IV which allows for more storage on board the vehicle with less space being taken up (in comparison to a single larger tank of same capacity) and a reported gravimetric capacity of 5.7 wt.% at 700 bars (Toyota, 2018). In short, the %wt. notation normalises the amount of fuel carried by the container by dividing the weight of the canister itself, where 5.7%wt results in 5.7 kg of hydrogen per 100 kg of the canisters weight. In comparison Type I storage containers usually have a gravimetric capacity/density of 1wt% (Barthélémy, n.d.). The type V storage tanks are made of composite reinforced materials, but they do not need to have an inner liner (Pohl & Ridell, n.d.). In an article from Composites World it states that the company Composite Technology Development, Inc. (CTD) has developed liner less type V tanks that "are expected to range from 15 to 20 percent lighter than their nearest Type IV cousins" (Legault, 2012).

For each of these types of storage methods (Type's I-V) there are some issues ranging from embrittlement of metal lined canisters to the high cost of manufacturing due to composite materials being used. The type of canisters that use metals (solely made of metal like Type I) or metal liners (Type II and III) can have problems when the hydrogen pressure inside them becomes too large. "Unlike other gases, hydrogen can damage the physical and mechanical properties of metals due to embrittlement: hydrogen atoms can dissolve in metal lattice and accumulate in disturbed lattice regions, thus impairing the main mechanical characteristics." (Carcassi & Fineschi, 2005). Furthermore, in a report from Dr. Stetson it was pointed out that the main reasoning to why the composites tanks are so expensive is due to the high costs of the composite materials themselves and their processing (Stetson, 2015). Finally, in composite tanks with inner linings such as Type IV, there have been cases were hydrogen gas was able to get in between the composite tank and the inner layer. As a result, this meant that during discharge of the tanks, the inner liner would buckle/collapse. Due to these mechanical stresses and fatigue movements of the liner would render the tank useless and unable to perform as intended (Wong, 2010). For a clearer picture of such a case, the author suggests the reader to look at the figure on page 11 of the referenced report (Wong, 2010).

1.8 Solar Cells

In the solar cell review by S. Sharma et.al the most common types of solar cells are analysed and explained. Table 7 shows a summary of the solar cells that were discussed and presented in the S. Sharma et.al paper (Sharma et al., 2015).

Table 7: Comparison of various type of solar cells. Source of values: (Sharma et al., 2015)

	1st generation solar cells (wafer based)		2nd generation solar cells (thin film)			3rd generation soalr cells (new emerging technology)				Perovskites
Number [-]	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Single/Mono-crystalline silicon PV	Poly/Multi-crystalline silicon PV	Amorphous Silicon thin film (a-Si) PV	Cadmium Telluride (CdTe) PV	Copper Indium Gallium Di-Selenide (CIGS) PV	Nano Crystal Based PV	Polymer Based PV	Dye sensitized PV	Concentrated PV	
η_el [%]	17-18	17-19	4-8	9-11	10-12	7-8	3-10	around 10	40	31
Cost [-]	2 x more expensive than thin film	Cheaper than (1), more expensive than thin film	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of conventional silicon cells	1/2 the cost of convention al silicon cells
High temperatures tolerance [-]	Little tolerance to high temperatures	Little tolerance to high temperatures	Good tolerance to high temperatures and cool temperatures	Good tolerance to high temperatures and cool temperatures	Good tolerance to high temperatures and cool temperatures	Excellent thermal balance/stability	Little tolerance to high temperatures conditions	Little tolerance to high temperatures conditions	Excellent thermal balance/stability	Excellent thermal balance/sta bility
Comment	Oldest solar cell type	Single most sold kind and best economical choice (around 48% of all PV's produced in 2008)	Needs large space and long installation time	Toxic as it uses Cadmium	Some CIGS can possibly have 20% electrical efficiency	Generally referred to as Quantum dots (QD) solar cells Needs large space but little installation time	Needs little space but little installation time	Needs large space but little installation time	Needs large space and long installation time	Latest technology needs minimal space and little time

The reasoning behind showing such a table is to show that there are multiple kinds of solar cells, but some are more applicable and widely used today. In the remainder of the report the type of solar cell that will be discussed (its data such as efficiency) will be type (2) from table 7. The multi-crystalline type is chosen as it has a relatively good electrical efficiency and also is one of the most produced and thus sold units allowing for a greater potential of finding such a unit in Sweden (bringing the theory in the paper closer to reality).

2 Technical analysis

With the multiple values and technologies mentioned in the background section of the report, a more concise list of what was used in the remainder of the report will be listed here, with less explanation as it is felt that the reader has a general understanding of the various technologies from the text in the previous section.

The expected hydrogen demand for the hydrogen truck will be 28 kilograms per day with a storage pressure on board of 350 bar. The assumed type of storage that will store the hydrogen on the ground until it is refuelled to the truck will be compressed hydrogen in type I storage canisters. This was assumed as this would simplify the processes of transferring the hydrogen onboard the truck requiring primarily a compressor to increase the pressure. The storage canister on the truck is assumed to be type IV, with a total volume of 1 200 L evenly divided across six tanks. The energy needed to compress the hydrogen and increase its pressure to 350 bar is assumed to be around 14% at 350 bar of the total energy of gas that is stored (i.e. 28kg). Using the energy density of hydrogen in lower heating value (33.33 kWh/kg) results in 4.7 kWh/kg of hydrogen energy needed for the compressor work (0.14x33.33 = 4.7). The compressor itself is seen as being electrically driven either by electricity from the grid or from solar cells. The electrical energy required to compress the hydrogen using the higher heating value would result in the equivalence of 5.6 kWh/kg of hydrogen energy. The assumed energy needed to compress the hydrogen that will be used in the report will be with the higher heating value, as it can only be assumed that the gas is brought back to its temperature prior to compressing.

As the fuel cell used on the truck is a PEM fuel cell which requires very clean, closer to pure hydrogen, along with the desire to guarantee producing green hydrogen, electrolysis will be assumed to be the technology providing the hydrogen. The electrical efficiencies of the electrolysers are assumed to be around 85% which translates to an energy demand around 47 kWh/kg of hydrogen. This value is most probably the higher heating value as 85% of 47 kWh/kg results in 39.95 kwh/kg which is very similar to the higher heating value of hydrogen (HHV 39.72 kWh/kg).

Furthermore, a possibility of producing green electricity using solar cells on Renova buildings and possibly its landfill is also analysed. Among the solar cells mentioned in the background section, multi-crystalline silicon PV's are assumed to be the solar cell used, primarily due to the major amount of this type of PV that is in the market. The electrical efficiency of these types of cells is assumed to be around 18%.

Besides the solar cells, electrolyser and compressor, ancillary equipment are also needed (such as dryers, coolers etc). which are referred to as balance of plant (BOP). To take into account the BOP's energy need an additional 10% of the energy demand for the electrolyser and compressor is assumed. Overall, this results in an electric energy demand of 57.9 kWh/kg of hydrogen produced (47 kWh/kg (electrolysis) + 5.6 kWh/kg (compression work)) x (1+0.1) (BOP) = 57.9 kWh/kg of hydrogen). An example could be given where having solar cells with an electrical efficiency of 18%, that cover 10 m^2 and receive around 1000 W/m^2 (10 kW/m^2) sunlight would require around 32,17 hours of sunlight to produce one kg of hydrogen gas (18% x 10 kW /100 % = 1.8 kW_{el} , 57.9kWh / 1.8kW_{el} = 32.17 h).

3 Possibilities of refuelling the hydrogen truck

The following section will analyse three methods for providing hydrogen to refuel the hydrogen driven refuse collector. The methods range from the available refuelling stations that exist today or are planned to be put in operation, to buying hydrogen in compressed gas canisters and by using a compressor to increase the hydrogen gas pressure to 350 bar which is stored on board the vehicle and thirdly producing their own hydrogen. Finally, the third method would be if Renova would produce their own electricity either by installing solar cells on the rooftops of their buildings and/or try to utilise some of the district heating energy that is cooled in the summer at Sävenäs to produce electricity. The electricity could then be used to produce hydrogen on a hydrogen refuelling station that would be owned by Renova and would have the capability of producing hydrogen through electrolysis.

3.1 Hydrogen refuelling stations available today or planned to be in operation

When it comes to hydrogen refuelling related updates within Sweden, the most current way to gather information is from an ideal association (can also be called a non-profit organisation) called Hydrogen Sweden. From the author's understanding, Hydrogen Sweden's aim is to promote a hydrogen society, their aim is to act as an initiator, coordinator and knowledge spreading about hydrogen (Vätgas Sverige, n.d.-a). Furthermore, Hydrogen Sweden sees that the hydrogen and fuel cell areas are developing strongly and together with other technologies could enable a more sustainable and energy efficient energy supply for the future (Vätgas Sverige, n.d.-a). Additionally, when it comes to hydrogen refuelling stations Hydrogen Sweden is part of European initiative that would like to increase hydrogen vehicle movement by having hydrogen refuelling stations strategically located across Europe to begin with (scandinavianhydrogen.org, n.d.). The project is called the Nordic Hydrogen Corridor (NHC) project which is partially funded by an EU fund that aims to interconnect Europe. The EU fund is called Connecting Europe Facility (CEF) and is a funding body of the European Union which aims to promote competitiveness, jobs, and growth through targeted infrastructure funding/investment at a European Level (Innovation and Networks Executive Agency (INEA), n.d.). With the Nordic Hydrogen Project, eight new hydrogen refuelling stations are planned to be built across Sweden (Vätgas Sverige, 2017). The city of Trelleborg in the South of Sweden is the first city that will get a hydrogen refuelling station due to the NHC project (Vätgas Sverige, 2020).

There are five hydrogen refuelling stations across Sweden which are shown on Hydrogen Sweden's webpage. Out of the five only four are in operation and are located in Umeå (northern part of Sweden), Arlanda (next to the airport in Stockholm), Sandviken (north of Stockholm) and Mariestad (found between Stockholm and Gothenburg)(Vätgas Sverige, n.d.-b). The stations in Arlanda, Mariestad and Umeå have a refuelling pressure only for passenger cars at 700 bar while Sandviken is the only one active that offers both 700 and 350 bar for passenger and heavy vehicles respectively (Vätgas Sverige, n.d.-c).

The fifth hydrogen station that is shown on Hydrogen Sweden's homepage is the hydrogen station on Hisingen in Gothenburg which is currently out of order (Vätgas Sverige, n.d.-c). As mentioned in the background section of the report, the interest by multiple actors has increased in the Gothenburg area due to the actual hydrogen truck that has been bought by Renova. The refuelling station on Hisingen is expected to become operational around July-August 2020 and have the capability of refuelling to 350 and 700 bar respectively (Vätgas Sverige, 2020a). A hydrogen refuelling station that is not mentioned on the refuelling webpage on Hydrogen Sweden is the one that OKQ8 is planning to build at Holmen next to Renova's headquarters and garage for their vehicles, however the inauguration date for this station is not set yet (Vätgas Sverige, 2020b).

3.2 Buying compressed hydrogen gas and using compressor to increase pressure of hydrogen gas

As hydrogen has been used throughout many industries for many years it is seen as an industrial gas that can be bought. Depending on the quantity needed it can be provided in smaller more portable canisters to large tanks on site refilled by truck. For the purpose of this project a temporary solution would be to have compressed hydrogen in cylinders delivered by truck to the company. This method will be referred as bundled canisters, where each bundle has 12 type I hydrogen canisters with a working pressure of 200 bar and capacity of 50 litres. To give a representation of the size and shape of such bundle units, the reader is directed to the webpage of PWENT which has multiple figures and dimensions of such units which are also representative of the EU norms (PWENT, n.d.). The maximum dimensions of these bundles are 2.1 m high, 1.03 m wide and 0.78 m deep; or a volume of 1.69 m^3 and a base footprint of 0.80 m^2 (PWENT, n.d.). Using the ideal gas law equation (1) with a pressure of 200 bar, a capacity of 50 L and assumed temperature of 20 °C the capacity of each canister is around 0.8 kg of hydrogen gas.

When it comes to gaseous hydrogen compression there are four main types of compressors (positive displacement or centrifugal types), the reciprocating-, rotary-, ionic- and centrifugal- compressors. The reciprocating compressors usually use an electric motor to drive a piston or diaphragm back and forth increasing the pressure of the hydrogen gas by reducing its volume. This type of compressor is the most common type when a very high compression ratio (outlet pressure divided by inlet pressure) is required. A rotary compressor uses meshing gears/vanes/screws to compress the hydrogen gas, but some issues due to the nature of hydrogen being so small requires high tolerances on such compressors. Ionic compressors have most similarities to a reciprocating compressor but instead of a piston an ionic fluid is used to decrease the volume and increase the pressure of hydrogen gas. Furthermore, ionic compressors do not need/require bearings and seals which are the most common fault issues of reciprocating compressors. Ionic compressors can be bought at the capacities and pressures needed by hydrogen refuelling stations. Finally, centrifugal compressors are the most favoured compressor types for pipeline applications/uses primarily due to the fact that they can have a moderate compression ratio while having a high throughput (for example kg of hydrogen per hour) (Department of Energy, n.d.).

A couple of companies were contacted and asked a few questions regarding hydrogen- and gas canister-supply. The questions can be seen in appendix B of the report, but it should be mentioned that none of the two companies answered all the questions. The two companies that were contacted were, The Linde Group and Air Liquide, which specialise in among other things, in providing gases in various qualities and quantities to multiple sectors/industries from academia to hospitals.

Regarding the response from The Linde Group there are possibilities of supplying hydrogen to refuel the refuse truck, but a compressor would be needed to increase the pressure. There are various qualities of gas that a customer can choose, and the typical notation is 3.0, 4.0 and 5.0. What this means is the purity of the gas is represented by the number of nines at a percentage level, for example 3.0 means a gas purity of 99.90%. Had the digit been different after the decimal instead of zero, for example, 4.8 the purity of said gas would be 99.98%. With this said to guarantee a good quality for PEM fuel cells the author would recommend grades higher than 4.0. Furthermore, it was pointed out that the grade that The Linde Group gives is the lowest guaranteed quality, therefore 3.0 would mean receiving a gas which is at least 99.9% pure. Additionally, The Linde Group has delivered the hydrogen refuelling stations in Arlanda and Sandviken. For the expected demand of 28 kg of hydrogen per day, it was recommended that a larger amount of canisters is supplied instead of the bundle units that have 12 tanks of 50 L capacity each or 0.8 kg of hydrogen gas at 200 bar. This larger unit can still be shipped by truck but contains 147 tanks of 50 L capacity and a total of 111.7 kg of hydrogen on board. Not all hydrogen should be expected to be extractable but almost four refuelling's should be possible. Finally, The Linde Group does not rent out empty canisters for the customer to store their own gases nor do they have compressors in their assortment (P. Gerdin personal communication, April 28, 2020).

Browsing The Linde Group's webpage a brochure was found were a customer could get help with their hydrogen projects, ranging from the gases to the complete hydrogen refuelling station. In the brochure two types of compressors are mentioned, an ionic pump for compressed gas and a cryogenic pump for liquid hydrogen. The author points this out not to contradict what was said during the personal correspondence but merely to show that other markets may offer a wider range of products from The Linde Group. In the brochure the footprint of the compression technology (cryogenic pump or ionic compressor) is at maximum that of a 40 ft container and the smallest around 14-20 ft container (The Linde group, n.d.). The size of a 40 ft container (outside measurements) is 12.19 m long and 2.44 m wide; with an area of 29.74 m^2 (Freight Finders, n.d.).

Assuming that the area of the larger hydrogen canister unit is in proportion to that of the bundle with 12 canisters it would have a footprint of 9.8 m^2. Combining the footprints of the hydrogen storage canisters and the compressor and no distance is needed between them, the smallest footprint would be around 39.54 m^2. As a rule of thumb, it could be said that if more hydrogen capacity is needed around 10 m^2 is required for an additional 110 kg of hydrogen of storage capacity (actually 9.8 m^2 and 111.7 kg).

In the case for Air Liquide the response was that they are in the early stages of learning how to use hydrogen as an energy carrier for Sweden. Therefore, they were not able to answer the questions. However, in Norway the company has been involved in a similar project for a couple of years and the Swedish representative would try to get some help from the Norwegian colleagues to hopefully be able to give some answers to the author's questions (P. Stjernberg personal communication, April 28, 2020).

3.3 Green electricity running an electrolyser and own hydrogen refuelling station

A possibility could be that Renova could own and operate their own hydrogen refuelling station. A meeting was held with Dr. Jimmy Ehnberg who is a researcher at the division of Electric Power Engineering at the department of Electric Engineering, Chalmers University of Technology where possible cases were discussed and analysed on how the electrical power could be supplied to the electrolyser unit. Figure 7 below illustrates the three cases that were developed at the meeting regarding electrical supply to the hydrogen refuelling station.

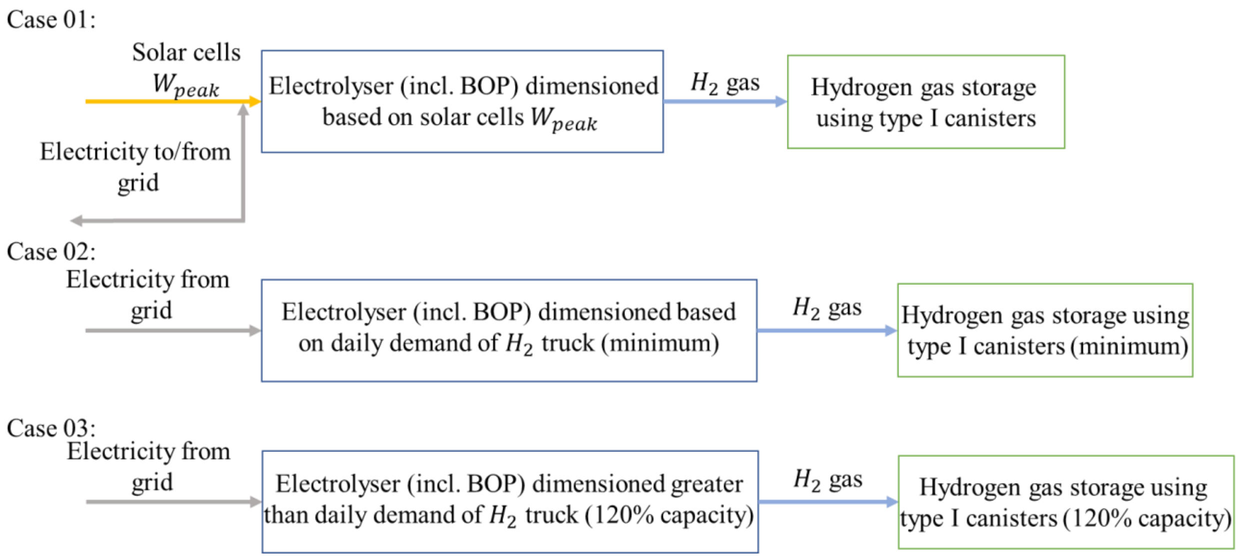


Figure 7: Three cases illustrating how the electrical supply and the design of the refuelling station could be and what the dimensioning factors are.

Case 01 from figure 7 would basically be built around the amount of solar cells installed and the expected peak power is primarily being used by the electrolyser and the remainder of the equipment needed to keep the operation running (BOP). The reason why the electricity grid is connected to and from the electrolyser is to be able to guarantee that there will always be electricity supplying the station even when the sun is not shining. An example where electricity from the grid would be needed is if the truck would need refuelling during the night. Alternatively, having solar cells being connected to the grid would allow the generated electricity to be sold to the grid generating an extra income for Renova. Even though the remainder of the plant would be dimensioned to take in all electricity from the cells, an assumption could be that some maintenance would be needed to be carried out on the station itself or the truck so being able to divert the electrical energy from the PV's to the grid would be beneficial.

Case 02 from figure 7 would only receive electricity from the grid and the primary reason was that this allows for simpler planning of the station's location compared to case 01which would require that a location has both solar cell capability and place for a hydrogen generating and refuelling station. The electrolyser and the remainder of the plant would be dimensioned after the daily demand of the truck itself (around 28 kg of hydrogen gas per day at 100% capacity). Furthermore, as the theoretical plant would be designed according to 28 kg/day the electrical demand would be known and the fluctuation in price throughout the year could be evened out to an average. This average price could be higher or lower at times compared to the spot market price. Using the value derived in chapter 2 (Technical Analysis) of the electrical energy demand being 57.9 kWh/kg of hydrogen and a demand of 28 kg per day would result in a daily electrical demand of 1621 kWh.

Case 03 from figure 7 would in theory have a larger plant than is needed for the daily demand, for example around 20% larger, and this would allow to more freely choose when to generate hydrogen. The electricity for the plant for case 03 would only be supplied by the grid and the reasoning is the same as in case 02 (simplifies location planning). Choosing when to generate hydrogen and being only connected to the grid would allow the plant to follow the electricity spot market price and when it is at a low enough price the generating unit would be run. Having around 20% more capacity could in theory keep up with the 28 kg/day demand and not have to continually be generating hydrogen (as in case 02). This would reduce the full load hours (FLH) of the plant but the economical savings from the grid would in theory outweigh this. Figure 8 below illustrates the electricity prices for SE3 region where Gothenburg is included for 2019.

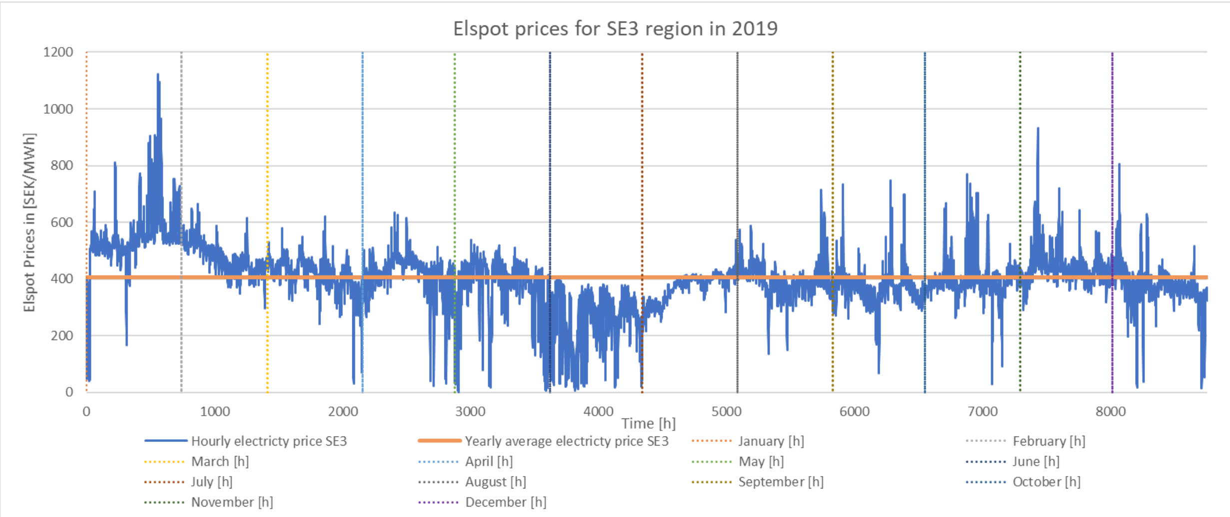


Figure 8: Hourly and yearly average electricity prices shown in blue and orange colour respectively. Source of values: (Nord Pool Group, n.d.)

The most expensive hour in 2019 was hour 560 (2019/01/24 from 08-09) with a cost of 1122.79 SEK/MWh. The cheapest hour in 2019 was hour 2908 (2019/05/02 from 04-05) with a cost of 1.28 SEK/MWh. Even though these are the extreme cases as can be seen from figure 8 (blue line) it can still be said that there are certain hours of the year that have drastic spikes (up and down) primarily the down dips seem to get closer to the minimum level. The orange line represents the yearly average for 2019 with a cost of 405.5 SEK/MWh.

Taking the daily amount of energy needed for case 02 and extrapolating it for a year (assuming non-stop operation) would cost around 240 000 SEK/yr. (239 949 SEK/yr.). Dividing the cost by the amount of hydrogen produced in a year yields a price of 23.48 SEK/kg hydrogen. To get such a price in the case 03 scenario would require designing an optimisation program that would iterate until it reaches the lowest possible price and still meeting demand (some form of linear programming). As these are speculative prices and values, such a simulation was not done, but based on the assumption that being able to flexibly run the plant and still meet demand it is expected to show a lower cost for case 03 than for case 02. With this said, an assumption was made that being able to perfectly choose the lowest prices throughout the year could yield a cost reduction of about 20%, 324.4 SEK/MWh (405.5 x 0.8 = 324.4). With this assumed spot price, the yearly cost of the hydrogen would be 191 959 SEK/yr. or 18.78 SEK/kg hydrogen. Taking these prices (and assuming a currency conversion of 10 SEK = 1 €) to produce hydrogen comparing to the costs mention by Mr. van Hulst (1.5€/kg and 3.5-5€/kg for grey and green hydrogen respectively) puts these costs within the same ball park. However, the assumptions made for these calculations were quite simplified where no return on investment cost or maintenance costs were added. These would vary with the unit size, full load hours and maintenance intervals of the station or truck. Furthermore, comparing the consumption of the traditional refuse collector which was discussed in chapter 1.3 of the report (consumption 60L/100 km and 1900km/month) to the hydrogen truck the costs are quite similar. Assuming a month is 30 days the traditional refuse truck requires 38 litres per day of HVO biodiesel (1900km/month ÷ 30 days/month = 63.33km/day x 0.6 L/km = 38L/day) and the price of HVO 100 biodiesel from OKQ8 for companies is 14.81 SEK/L (2020/05/28 price) (OKQ8, 2020). This would mean that per day the fuel cost of the diesel truck would be 562.78 SEK/day (14.81 SEK/L x 38L/day = 562.78 SEK/day) and the hydrogen truck 657.44 SEK/day (28 kg/day x 23.48 SEK/kg = 657.44 SEK/day). The difference is less than 100 SEK (around 10€) which for a technology that is not fully developed and optimised can be seen as being quite competitive. The following section will try to identify possible locations at Renova that would help realise a hydrogen refuelling station that would resemble case 01 from figure 7 (green hydrogen production).

4 Own hydrogen generating and refuelling station

In the following section the possibilities that Renova has regarding places fit for solar cells or energy recovery at the Sävenäs waste to energy plant will be analysed. To begin with this analysis can be seen as a hybrid version of the three cases shown in figure 7 in the previous section, were the electrolyser could be powered by renewables or recovered energy (as in case 01) but dimensioned more similarly for the other cases (cases 02 and 03). To be able to reach a possible design suggestion, various parameters will be analysed from the solar cells, energy recovery availability and the availability of finished hydrogen refuelling stations that can be bought (so called turn-key solutions). The main reason on only focusing on turn-key stations is because it is not expected of the customer to need to gather various parts or components to make a refuelling station. For customers, whose main goal is not to run hydrogen stations but use hydrogen to meet their goals, turn-key solutions are felt to suit the case better. In the case of Renova, their main goal is to collect and safely handle waste and do it with the least impact on the environment. Hydrogen is seen as helping them reach that goal, but they only require that there is a way to refuel their vehicles.

4.1 Solar cell possibilities and energy recovery at the waste to energy plant

The Swedish Meteorological and Hydrological Institute (SMHI) have published the amount of solar energy/irradiation and number of sunshine hours expected by a region in Sweden. For the Gothenburg region the assumed number of hours of sunlight are around 1700 hours and a solar energy of 1000 kWh/m2/yr. (SMHI, 2017a, 2017b). Gothenburg Energi offer on their webpage the ability to see what the expected amount of solar irradiation can be on a building. For this algorithm to work the buildings need to be close to a public road, if not then there is no data for the building. The solar irradiation for the locations mentioned in the following section are either from Gothenburg Energi webpage or from the value of 1000 kWh/m2/yr. from SMHI.

In an energy education webpage regarding solar cells from the university of Calgary, Canada it explains the most optimal orientation that solar cells should have, to have the best opportunities to convert as much energy from the sun for the longest time. The sun’s rays need to hit the solar cells surface perpendicularly this can either be done by solar cells fixed to trackers (which would give the most amount of electrical energy produced but with a higher investment cost) or “fixed” non-tracking solar cells. As the report intendeds to analyse solar cells for building rooftops and/or on an inclined embankment, only “fixed” type solar cells will be assumed. For example, Gothenburg has a latitude of 57.7 which means that an ideal inclination for fixed solar cells is 57.7°. The direction that the solar cells need to face in the northern hemisphere is the geographic or solar south (the directions towards the South Pole) and the optimal angle is dictated by the latitude of the location. Depending on the use of the electricity from the solar cells other orientations than true south would be more beneficial (e.g. face more south-west would produce more electricity during late afternoon when it would be more beneficial for home owners) but with the assumption that the most energy regardless of time is desired the south orientation will be assumed. Furthermore, having a larger tilt angle compared to a shallower/smaller angel, also helps debris and dirt not collect on solar cell surfaces reducing the risk of blocking solar irradiation (Stenhouse et al., 2018).

4.1.1 Field trip to various locations operated by Renova

On Friday the 28th of February, a meeting was held between the author and Daniel Rodhe who is in charge of the landfills (Tagene and Fläskebo) operated by Renova. The meeting was held to discuss any possibilities of the landfills offering any areas that would be suitable for solar cells. Daniel mentioned that most areas at these landfills are still active. However, some embankments (walls to contain the material being landfilled) are completed and could in theory provide areas for solar cells. Figure 21 and Table 8 which are found in a later part of this report shows the embankment and the calculations done to find its area. Daniel pointed out that this embankment could be a possibility as it faces the correct direction for solar cells (south) and has a good inclination (reducing the risk of solar cells casting shadows on each other). With this possibility a field trip would help give an understanding of the size and slope of the embankment.

On Wednesday the 1st of April, a study visit was conducted to Tagene landfill with the help of Camilla Svensson. Camilla is the facility coordinator at Renova. Camilla and the author met in the morning at around 08:30 at Renova's waste to energy plant in Sävenäs were one of the company cars was used to drive to the landfill. Having discussed a little with Camilla about the project she also planned to show some other locations that may be suitable for solar cell installations. Primarily, the focus was on the buildings rather than the landfill as Camilla mentioned that it is not allowed or would be very difficult to install solar cells due to the fact that a geopolymer textile is used to cover the landfilled material and that should not be disturbed/punctured by for example a foundation or poles to hold the cells.

From the waste to energy plant the first location that was visited was the second landfill that Renova has which is called Fläskebo, were they landfill hazardous waste such as the gypsum that is extracted from the flue gas cleaning system at the waste to energy plant. Additionally, at Fläskebo they also landfill contaminated soils that is brought in from amongst others construction sites. As the nature of the landfill is to have vast open spaces were materials are deposited, this causes an issue with high wind speeds being quite frequent. At Fläskebo, they have three structures that are used for various reasons and are built differently as such. To begin with they have the weighing station were the controllers make sure that they weigh the trucks when they come in and leave. This building has some possible roof areas that could bear solar cells, but unfortunately the angle of the roof is sloping away from the sun, i.e. it is not southwards facing, but the roof angle was quite shallow/little. This was observed on the lower level of the building. The second level roof was not viewed during the visit as the author failed to notice that it was possible to access it without having to request for a ladder. Figure 9, shows the three buildings that were viewed at Fläskebo landfill. Building "1" is the weighing station's building were from the shadow casted in the image two levels for the roof can be distinguished. Unfortunately, it was unable to extract from Gothenburg Energi's solar map on how much the irradiation is for these buildings.

Figure 9: Fläskebo landfill and the 3 buildings that were viewed. Source of image: (Google Maps, 2020a)

The second building (marked “2” in figure 9) that is at Fläskebo is a water treatment building that discussing with Camilla she mentioned that it was recently finished and does not have any plans for the short future in being renovated. The building is quite high up (rough estimate approx. 8m) has a relatively flat roof, but it has short walls on the southwards facing side meaning that if solar cells were to be installed either the wall could possibly be lowered even further or removed or the cells raised higher to fully maximise the hours of sun they could receive. Finally, a large tent (marked “3” in figure 9) is used to store unknown soils until samples and tests are made to determine if they can be deposited in the landfill. The tent seems to be a structure that is not permanent as the structure is comprised of a plastic cover over a metal frame. If the tent is planned to be converted to a permanent structure this would definitely be a great opportunity to have the roof facing favourably towards the south were solar cells could be installed. Finally, it should be noted that amongst the three structures the tent has the largest footprint, which can easily be seen in figure 9. Using the measuring distance tool in Google maps for figure 9, the approximate size of the structures (from a birds eye view measurement) are 187 m^2, 112 m^2 and 1200m^2 for buildings 1-3 respectively. As this is a bird’s eye view measurement, this does not take into account for the curvature of the tent for example or the different levels between the rooftops for the remaining buildings. Figure 10 below shows the images that were taken on the day of the study visit.

Figure 10: Lower roof level of weighing station building (left) and water treatment building and temporary storage of unknown soils tent at the back (right).

The above figure illustrates the inclination of the roof of the weighing station and how it is sloping towards the wrong side (regarding optimal inclination for solar irradiation). The two buildings, on the right of figure 10 show approximately the size and different roof levels for the water treatment building and the curvature of the tent that is used to store unknown soils. Please observe that the two buildings in the figure above are not in close proximity of each other which would give a false sense of size for the two. The tent is further away from the water treatment building in the image and at this angle they seem to be similar in size.

After leaving Fläskebo landfill, we drove towards Tagene, but on the way we quickly passed by some other premises that Renova has. The first place we passed by was the facility that Renova uses to bale amongst other plastics that have been sorted, and cardboards, the place is usually referred to as Rödingen. Camilla mentioned that there are quite a few equipment that are used there that are powered by electricity. We were unable to enter the premises to get a more detailed analysis of the facility but it was easy to see from the outside that the building is large, probably larger than the tent at Fläskebo, and that the roof has some sides that are facing the south. However, the side of the building could also offer some possible mounting points for solar cells on a ledge (cantilevered solar cells). Even though the roof may be partially facing the south, the inclination that could be understood from the ground seemed to be quite low, this means that at least a partial part of the roof could possibly have solar cells (maybe at least to meet the demand of the equipment on location).

Figure 11 below, illustrates the approximate height of the buildings and the possible inclination of the roofs at Rödingen.

Figure 11: Picture of Rödingen balling station taken during the fieldtrip to Tagene.

As can be seen from figure 11 above, on a sunny day the whole façade receives plenty of sunlight, without having any major shadows. These areas, especially the blue metal panels could be a good candidate to install solar cells. Maybe these solar cells would be enough to power some lighting that the building would need, during a day, for example an office.

To help get a sense of the size and inclination of the roofs, a Google Earth image (left) and an expected solar irradiation level (right) is provided below in figure 12.

Figure 12: Rödingen balling station rooftop and cross-sectional view (left). Source of image: (Google Earth, n.d.-b) Solar irradiation potential for the rooftop at Rödingen (right). Source of image: (Göteborg Energi, 2020b)

It can be seen from figure 12 that the assumed low inclination of the roofs at Rödingen is reinforced by the image to the left. Additionally, from the solar map on the right hand side of figure 12 it can be seen that the roofs at Rödingen have sections that are expected to receive the maximum and a step below maximum in solar irradiation (except for a small section due to the different roof levels may result in some shading). This makes it a great candidate for installing solar cells, not only to provide energy for the electrolyser, but also helping run the equipment at Rödingen itself. Once again, using the measurement tool provided in Google maps, an approximate size for the roofs at Rödingen are estimated to be around 6900 m^2.

After having briefly passed by Rödingen baling station we drove down the road to another facility of Renova called Marieholm. The following figure 13 shows some of the buildings and their different roof levels at Marieholm along with the entrance.

Figure 13: Marieholm station which was visited during the field trip and with the different levels of the roofs of the buildings.

Discussing with Camilla she explained that at Marieholm Renova processes greenery from garden waste turning it into soil and pre-treatment for biogas production (basically the slurry mixture that is used by the biogas plant is prepared). Driving around the Marieholm premises it was observed that there are no obstructions from the surroundings regarding solar irradiation to the buildings. To help the reader get a perspective of the size of Marieholm in terms of area and buildings on site figure 14 shows a Google Earth image.

Figure 14: Marieholm is one of the visited locations during the field trip and to the left is the compost piles and to the right the buildings there. Source of image: (Google Earth, n.d.-c)

Looking at figure 14, it can be seen that almost all roof tops at Marieholm are connected, meaning there is no single self-standing structure (except the garage with the dark roof on the top right of the figure). This is interesting as this could possibly make it easier to install the solar cells and use a lot less ancillary equipment such as inverters that are needed to convert the electricity from direct current (DC) to alternating current (AC). Besides the potential for a centralised connection point between the solar cells and the electricity conversion an estimate of the solar irradiation potential is also needed to help in deciding whether or not the buildings are suitable for solar cells. The solar irradiation for the buildings at Marieholm is illustrated in figure 15.

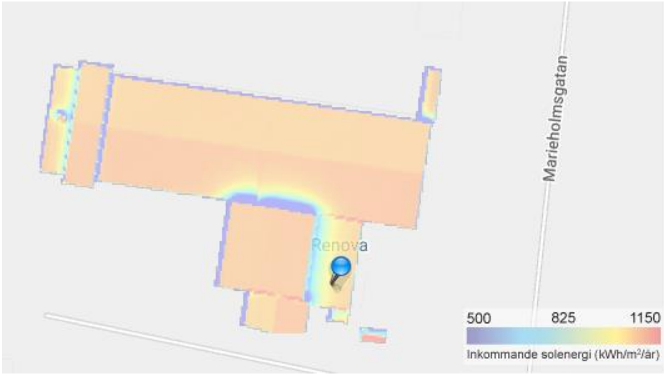


Figure 15: Approximate solar irradiation that can be expected on Marieholm's buildings. Source of image: (Göteborg Energi, 2020c) .

From figure 15 it can be seen that most of the areas at Marieholm can be assumed to receive the most irradiation from the sun within the Gothenburg area. Some parts of the larger building may not receive a good amount of irradiation, and this is due to the fact that the larger roof is slightly lower than the building in front of it (seen more clearly in figure 14). But overall, as most of the roofs have an orange/ coral colour, it would be of interest to further investigate this location for solar cell installation.

An estimate made using the measuring tool from Google maps regarding the square metres of roofs available at Marieholm, indicate that around 3000 m² of roofs are available (of those seen in figure 15). This does not take into consideration the different elevations that the various roofs have between them. Additionally, the calculation of the available roofs does not take into consideration the garage found in figure 14 (dark roof, top right of figure). This was intentionally done, as it was pointed out when we finally reached Tagene that the reality and the Google maps images were quite different (discussed further down). As the author personally did not notice or see this structure during the field trip, it is not comfortably felt that this could be taken into consideration of the suggested roof top areas. If this structure does exist, an approximation of the area would mean an additional 750 m² (with excellent expected solar irradiation) for solar cells exists.

The facility has multiple buildings at various levels but using Google Earth and the understanding from being on location it can be said that there is a potential for solar cells. Some renovation was being done to one of the roofs at the time of the visit and this is an unclear point that would need to be investigated if there are any plans for the near future to renovate any of the roof top areas at Marieholm. If a renovation might be in the plans for Marieholm or any building for that matter, it would not be a bad idea to try and combine the two (renovation and solar cell installation).

Finally, after having been to Fläskebo landfill, Rödingen baling facility and Marieholm facility we finally arrived at Tagene. Tagene is not only a landfill, but it also serves as a short-term storage for the waste that is not intended to be incinerated at Sävenäs at the time of collection. Additionally, it is used to sort the bottom ash also called slag that comes out of the furnaces at Sävenäs, this is done to extract any metals from the ash that can then be recycled and reused. Furthermore, Tagene offers the ability for refuse trucks to empty the collected waste into large containers that can then be transported more efficiently to Sävenäs for incineration, this process can also be referred to as transhipment. Finally, Tagene offers a recycling centre were private individuals can sort and dispose of their waste in a safe and orderly manner. Figure 16 below, shows a birds-eye view of Tagene landfill with certain regions highlighted in red.

Figure 16: Birds-eye view of Tagene landfill facility. Source of image: (Google Earth, n.d.-a).

From figure 16 it can be seen that there are six regions that are marked (numbered and highlighted in red circles). The first area is where the short-term storage for the collected refuse is baled, stored and can be approximately found at Tagene. Speaking with Camilla it was pointed out that the bales are used to evenly compress the soil/landfill beneath them so as to push out any possible air pockets thus allowing for more efficient use of the landfill. Additionally, the second marked area is the buildings were the garage/workshop is found and the weighing station were the personnel monitor the vehicles weights coming in and going out. Furthermore, the third location illustrates the recycling centre that people can use to sort their waste into specific containers. The fourth marked location is the building that the refuse trucks use to transfer the collected refuse to larger containers, referred to as transhipment station earlier. The fifth highlighted area represents the area that the slag from Sävenäs is piled up to dry and then screened to remove any valuable metals. Finally, the sixth location that is marked in figure 16 represents the hill that was intended to be measured and compared to the Google maps image shown in figure 21 and discussed with Daniel Rodhe.

Arriving at Tagene, it was quickly understood that it covers a large area and serves multiple functions. Camilla drove us around a little bit, as we had a saloon car and due to the road conditions a better suited vehicle such as a pick-up would have made it possible to drive around more of the landfill. Regarding buildings at Tagene, there are a few that could possibly be fit for solar cell installation. As at Fläskebo, they have a weighing station at Tagene as well serving the same function of controlling the content and weight of the vehicles coming and going (marked as nr. 2 in figure 16). Additionally, the transhipment station is quite large however the roof has a slope towards the east (marked as nr. 4 in figure 16). Thirdly, a building was seen from entering the facility, were it seems to be quite new, but the orientation of the roof faces north-east. Figure 17 below illustrates the new building that was seen from the entrance to Tagene.

Figure 17: A new building that is found at Tagene, with a roof orientation towards north east.

The renovation plans for the weighing station and transhipment building are unknown. Discussing with one of the personnel at the weighing station it was pointed out that the environment is quite harsh in regard to the amount of dust that can be generated at times. The reasoning was that to sort the metals out of the slag, it needs to be dry enough so that the non-metallic particles are not attached to the metals. When the non-metallic particles dry, they liken the properties of sand/ dry clay in how easily they can become airborne and also how hard they become once dry and baked in the sun. When the sorting equipment is run large clouds of dust can form. This could pose several issues for the solar cells. One could be that the amount of solar irradiation is drastically reduced due to the dust in the air which would in turn reduce the amount of generated electricity. A second issue could be that the dust settles on the solar cells which would also reduce the electrical production, but it would also increase the need for cleaning of the cells increasing the running costs. Camilla and the person working at the weighing station pointed out that the environment is basic meaning that it causes issues for metals (chemically reacts with them), were they start to corrode unless a protective cover is used. An example was given were the pickup that Tagene has which is not that old but due to the aggressive environment it has already started to have problems with corrosion attacking the vehicle frame and panels. This could also be an issue that the solar cells could suffer from. Maybe not the panels directly as the frame is made of aluminium and it has a glass cover on top, but the support structure holding the solar cell would have to be corrosion resistant at least.

As this landfill is also large, it was clear that large gusts of wind are possible. At the proposed site for solar cells on the bank of a hill (marked as nr. 6 in figure 16), it was self-evident that the inclination of the hill is much steeper than could have been guessed from looking at the Google -Maps and -Earth images. Figure 18 figure 17 below tries to illustrate how steep the hill actually is.

Figure 18: Picture taken at the top part of the hill with Camilla Svensson standing at the bottom of the hill.

It can be seen from figure 18 that the hill is quite steep and it should also be pointed out that the phone used to take this picture was around 20 centimetres from the ground (i.e. eliminating the added inclination difference that could have been added if taken at standing height).

Additionally, it was pointed out that the Google Earth and Google maps images are not continuously updated as the flaring station is shown to be at the base of the hill (online) seen within the yellow circle in figure 21, but in reality it has been moved to a section further up on the hill. Camilla mentioned that this was done as the road going up to the landfill is quite narrow and it is planned to be expanded to accommodate large trucks being able to meet and pass each other. Figure 19 below shows the work done to the moved flaring station and the work done to the road.

Figure 19: Panoramic image showing the moved flaring station and the road work done at the bend of the road.

From figure 19, there are 4 marked areas, where the first marking illustrates the flaring station moved to a higher level up on the hill. Additionally, the timing of the visit was good as this gave an opportunity to see and get an understanding of at least the top layer above the geotextile that is used to cover the landfill. The geotextile is marked as number 2 in figure 19 and number 3 is finely ground stone that is place just below and above the geotextile protecting it from any rocks that can be found in the top soil (marked as number 4 in figure 19). Roughly speaking, the approximal amount of topsoil (marked as number 4 in figure 19) could be around 0.9-1 metres.

Camilla Svensson pointed out that the slope has many layers (not just the ones seen in figure 19) were the sorted ashes are contained and a geotextile fabric (marked as nr.2 in figure 19) which is used to contain water runoff and keep rainwater from passing through. A layer of topsoil is deposited (marked as nr.3 in figure 19) on top to keep the fabric in place. Camilla explained that the slope needs to be monitored/guarded to make sure that no trees grow as long strong roots can damage the fabric. This is also an issue that would be faced if solar cells were to be installed as the topsoil layer is not deep enough and puncturing the fabric is unacceptable. Camilla mentioned that the sorted ash might contain some air pockets which after a long period can cause movement/shifting of the soil. Basically, due to sedimentation, the topology of the hill can change, and this also adds to the reasoning of being able to monitor the slope. Having said that, the positive aspects of the hill is that it is facing the south allowing for favourable solar conditions. Also, there are no large structures or trees close by that could cause shadows during the day. Having discussed the idea with Camilla of possibly installing solar cells on the landfill hill, with the mentioned reasons above, this idea may not be the first best alternative for installing solar cells. However, if there was a solution that allowed the installation of the solar cells without penetrating the ground and yet being able to withstand strong winds and not being affected by the aggressive environment this could be an option. A novel idea that was suggested by Camilla would be to have smaller solar cells that mimic the pattern of a mosaic that would allow the following of the contour of the hill better. Having taken all of this in, and with the time available, a small section of the hill was measured compared to the one suggested from the Google Maps image. The measurement was done to be able to compare how big of a difference the birds eye view area differs from the actual area due to the inclination of the hill. Figure 20 tries to give an illustration of the steepness of the hill, and in the top right part of the figure, a pile of drying bottom ash from Sävenäs can be seen.

Figure 20: Panoramic image showing the hill at Tagene and a pile of drying bottom ash in the background.

As mentioned earlier a small section of the hill was measured. However, due to the method used to calculate the theoretical area available this was not able to be reproduced on the day of the field trip. Instead a section that covers several areas of the theoretical area was done at once with sections smaller than the theoretical area. This was done as there is work being done to some of the sections of the hill that were thought to be available before and due to the deviation from reality and online imagery. Overall, out of the sections that are drawn in the theoretical image sections T2 & T3 can be seen as too close to the new road construction and thus should be eliminated altogether. To be able to bring theoretical and reality closer an area shrinkage of around 25% is highly recommended.

Figure 21: Theoretical areas for solar cells at Tagene. Source of image: (Google Maps, 2020b)

On some parts of the hill at Tagene the inclination would change. To give an indication of the inclination of the hill a pre-installed app from Apple on the iPhone called “measure” and choosing the option called “level” was used. Measuring at a few spots on the hill (guessing around areas T4 and T5 in figure 21) showed that the angle varied from 20°-32°. In Google Earth it was observed that at the current position of the cursor, looking at the bottom right of the webpage the metres above sea level is shown. With this in mind and an accuracy close to the nearest metre, an approximal inclination of the hill at these areas was found to be around 20°. Table 8 below, shows the completed table and the proposed area after making the changes that were felt necessary after the field trip.

Table 8:Tagene hill measurements showing the theoretical values, the comments and final area after the field trip.

Area	L1 [m]	L2 [m]	L3 [m]	s (herron's formula) [m]	Area [m²]	Diff. Actual vs theoretical	Inclination [°]	Proposed area [m²]
T1	20	33	0	0	660	-	calculated 17	495
T2	60	9	54	61.5	191	Too close to work done, remove	-	0
T3	54	57	9	60	235	Too close to work done, remove	-	0
T4	57	60	92	104.5	1662	Conservative side shrink by 25%	on-site 20-27	1246
T5	60	28	67	77.5	840	Conservative side shrink by 25%	on-site 20-32	630
T6	28	30	25	41.5	326	Conservative side shrink by 25%	calculated 16	245
T7	30	26	27	41.5	328	Conservative side shrink by 25%	calculated 16	246
T8	26	71	65	81	844	Conservative side shrink by 25%	calculated 16	633
T9	71	23	66	80	758	Conservative side shrink by 25%	calculated 17	568
T10	23	26	18	33.5	202	Conservative side shrink by 25%	calculated 17	152
T11	26	27	20	36.5	245	Conservative side shrink by 25%	calculated 17	184
T12	27	24	19	35	222	Conservative side shrink by 25%	calculated 17	166
T13	24	38	24	43	279	Conservative side shrink by 25%	calculated 16	209
T14	38	22	26	43	277	Conservative side shrink by 25%	calculated 13	208
T15	22	25	26	36.5	253	Conservative side shrink by 25%	calculated 14	190
T16	26	59	35	60	226	Conservative side shrink by 25%	calculated 12	169
T17	59	12	51	61	244	Conservative side shrink by 25%	calculated 11	183
Sum					7790			5524

Initially the theoretical area was calculated by measuring the three lengths for each triangle (using the Google Maps measurement tool) and by using heron's formula (geometrical formula). Heron's formula is

$$Heron's\ Formula: Area = \sqrt{s(s-a)(s-b)(s-c)}\ (2)$$

$$S = \frac{a+b+c}{2}$$

where a, b and c represent the three lengths that make up the triangle. As the theoretical measurements made were felt to be too optimistic some changes were made when calculating the final proposed available area, mainly by reducing the area by 25%. The proposed area available for solar cells at the Tagene landfill embarkment is 5524 m^2.

From a recollection during our many discussions with Camilla in the car during our filed trip, if it was understood correctly by the author, the way the fullness (state of being filled to capacity) of the landfill is measured is in vertical height (i.e. how much material has been used to build up the landfill/ landscape). With this recollection, the reason why, the angle is decreasing in table 8, is because the peak that was measured from Google Earth regarding to what height this hill should be filled was measured to be around 60 metres. With this in mind as the elevation increases (seen from the road going up the hill in figure 19) less and less material could be used to fill up the hill. Overall, it can be seen from table 8 that the total available area has decreased quite drastically, however having performed the study visit valuable insight was given which is seen as allowing with a larger certainty to say how much electricity could be expected to be produced from this site.

Table 9 below, illustrates the structures and the yearly expected electrical supply if solar cells were installed on them.

Table 9: Expected electrical output from various structures from the study visit.

Structure [-]	Area [m²]	Yearly irradiation energy [kWh/m²/yr]	Electrical output [kWh/yr]
Fläskebo building 2	112	1000	20160
Rödingen	6900	1000	1242000
Marieholm	3000	750	405000
Tagene embankment	5524	1000	994320

In table 9 only the second building from Fläskebo landfill was used as the other two structures had the wrong inclination or were unfit for solar cells (plastic tent). The solar irradiation value used was from the SMHI webpage as the building is found in a private area. The same assumption (solar irradiation) was used for Tagene as it is also found in a private area. For Rödingen and Marieholm the Gothenburg Energi irradiation values were used, and an average was calculated. The fact that various parts of the buildings are expected to receive varied amounts of solar irradiation and to compensate for this the average was calculated. Overall, the total area from these four structures is around 15536 m^2 with an expected electrical output of 2.66GWh/yr.

It was quite difficult to analyse all these locations all at once and visiting them for the first time was quite overwhelming with a lot to take in. Simply put a lot was taken in but not all information and analysis can be seen as successfully collected and utilised. However, with the equipment at hand and time available it is felt that a step towards going from theoretical calculations and areas to actual ones was brought closer than before. Having the opportunity to speak with Camilla Svensson and the person at Tagene gave invaluable insight to things and issues not thought of before, such as the dust and corrosive environment. Additionally, it was good that the field trip was conducted as this also pointed out that what is depicted by Google Earth is not always the current situation for that location.

4.1.2 Buildings found at Renova's headquarters

When it comes to the buildings found at Renova's headquarters, figure 22 below illustrates them with red borders and green labels.

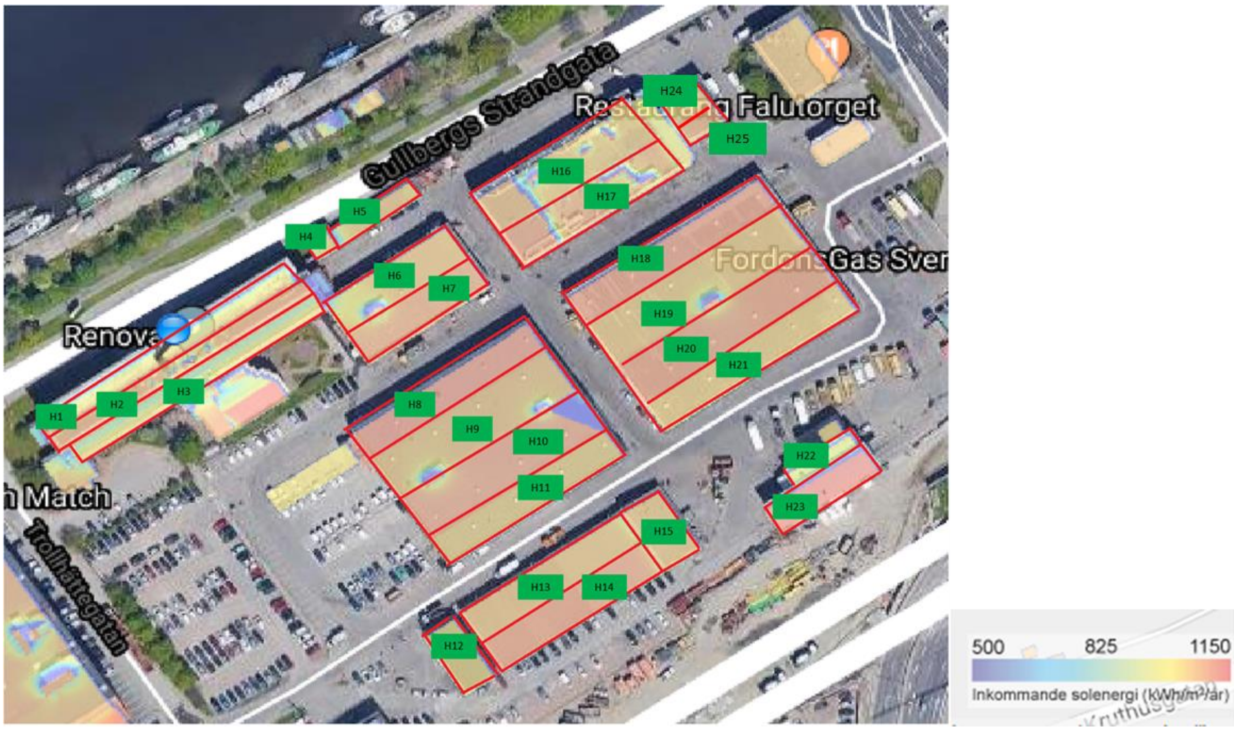


Figure 22: Buildings found at Renova's headquarter and their expected solar irradiation energies. Source of image: (Göteborg Energi, 2020a)

25 sections can be seen in figure 22, and the divisions were made to best match the solar irradiation that covers these sections. Table 10 below, illustrates the theoretical measurements taken using the Google Maps tool to measure the red borders length. Additionally, the areas are calculated along with used values for yearly irradiation and the expected electrical output.

Table 10: Theoretical measurements of the buildings found at Renova's headquarters.

Section	Length [m]	Width [m]	Approx. available [%]	Area for PV [m^2]	Yearly irradiation energy [kWh/m²/yr]	Electrical output [kWh/yr]
H1	87.35	6.4	50	279.52	975	49056
H2	90.35	5.65	50	255.23875	1100	50537
H3	86.55	5	60	259.65	975	45569
H4	7.8	7.8	90	54.756	975	9610
H5	27.8	6.25	90	156.375	975	27444
H6	42	11.5	85	410.55	975	72052
H7	42	11.5	90	434.7	1100	86071
H8	62	10	90	558	1100	110484
H9	62	15	85	790.5	975	138733
H10	62	15	85	790.5	1100	156519
H11	62	10	85	527	975	92489
H12	10	22	95	209	975	36680
H13	55	12	95	627	975	110039
H14	55	12	95	627	1100	124146
H15	13	22	90	257.4	975	45174
H16	54	12	20	129.6	975	22745
H17	54	12	15	97.2	1100	19246
H18	68	10	90	612	1100	121176
H19	68	15	80	816	975	143208
H20	68	15.5	80	843.2	1100	166954
H21	68	10	90	612	975	107406
H22	23	5.5	90	113.85	975	19981
H23	35	9	90	283.5	1100	56133
H24	13	7	60	54.6	975	9582
H25	13	7	75	68.25	1100	13514
Sum				9867.38975		1834543

From table 10 it can be seen that most areas of the buildings at the headquarters receive almost the maximum expected solar irradiation and that there are quite a few continuous areas such as sections H8-H11 and H18-H21 are two buildings. These two buildings alone make up more than 50% of the total area at the headquarters (Holmen) and these would be two of the best candidates for solar cells to supply a hydrogen refuelling station. As these are theoretical values a more in-depth analysis was made whether the buildings are applicable for solar cells or if they are newly renovated. These questions were answered by Magnus Lundström who's position at Renova is to manage/refine Renova's properties but also change the properties for the operational needs that may come/arise.

On Friday the 3rd of April 2020 a meeting was held with Magnus Lundström who is the property manager for Renova. The meeting was primarily focused on discussing the available roof areas for solar cells at Holmen. During the meeting, the Google Maps images with the various area allocations of the roofs at Holmen were used to fill in a table that was prepared earlier. The idea with the table was to try and verify the assumptions made during the theoretical part of the project. Additionally, the table would also help indicate various features that cannot be extracted from the Google Maps images, such as type of roofs. Table 11 indicates which parts were filled in with the help of Magnus Lundström. It should be noted that an indication of "-" in the table indicates that this point was not discussed explicitly during the meeting.

Table 11: Values & comments from the meeting with Magnus Lundström regarding Holmen rooftops potential for solar PV.

Section	Length [m]	Width [m]	Approx. available [%]	Area for PV [m^2]	Yrs left before renovation needed [yr]	Comment	Roof capacity [kg/m²]	Roof type [-]	Roof angle [°]	Obvious shadow areas [-]
Example	75	10	70	525	20+		200	copper sheet	5	chimneys, skyscrapers
H1	-	-	-	-	-	H1,H2,H3 not recommended because too much stuff/equiptment & 3 different elevations	All buildings have the carrying capacity to meet standards for snow and wind in Gothenburg	variant of tin roof	-	none
H2	-	-	-	-	-			variant of roofing felt	-	none
H3	-	-	-	-	-			variant of roofing felt	-	none
H4	-	-	-	-	-	H4,H5 low level maybe some shadowing from HQ building		variant of roofing felt	-	Maybe some shadows from HQ building
H5	-	-	-	-	-			variant of roofing felt	-	Maybe some shadow s from HQ building
H6	-	-	-	-	-	Expected renovation 2020 or 2021		variant of roofing felt	-	none
H7	-	-	-	-	-	Expected renovation 2020 or 2022		variant of roofing felt	-	none
H8	-	-	95	-	15+	H8,H9,H10,H11 renovated 2019 H8,H9,H10,H11 combined have an area around 3500 m²		variant of roofing felt	3	none
H9	-	-	95	-	15+			variant of roofing felt	3	none
H10	-	-	95	-	15+			variant of roofing felt	3	none
H11	-	-	95	-	15+			variant of roofing felt	3	none
H12	-	-	90	-	15+	Renovated 2020		variant of roofing felt	9	none
H13	-	-	90	-	15+	Renovated 2020		variant of roofing felt	-	none
H14	-	-	90	-	15+	Renovated 2020		variant of roofing felt	-	none
H15	-	-	-	-	-	-		variant of roofing felt	-	none
H16	-	-	-	-	-	Too much equiptment already		variant of roofing felt	-	none
H17	-	-	-	-	-	Too much equiptment already		variant of roofing felt	-	none
H18	-	-	95	-	15+	H18,H19,H20,H21 renovated 2020 H18,H19,H20,H21 combined have an area around 3500 m²		variant of roofing felt	3	none
H19	-	-	95	-	15+			variant of roofing felt	3	none
H20	-	-	95	-	15+			variant of roofing felt	3	none
H21	-	-	95	-	15+			variant of roofing felt	3	none
H22	-	-	-	-	10+	Not recently renovated but better material originally therefore expected longer lifetime		variant of roofing felt	-	none
H23	-	-	-	-	10+			variant of roofing felt	-	none
H24	-	-	-	-	-	maybe useful but smaller size & some equipment on roof		variant of roofing felt	-	none
H25	-	-	-	-	-			variant of roofing felt	-	none
Sum	-	-	-	-	-			variant of roofing felt	-	none

During the meeting, not all areas or columns were discussed and filled. The main reason was that the meeting was more of an overview/general discussion rather than going successively through the table, helping keeping a discussion going and getting more insights on how or why some proposed alternatives may or may not work. This meant that some questions were answered even if they were not explicitly asked or thought of before the meeting. For example just speaking of the project and some of the areas that Renova has, Magnus mentioned that he had spoken to Gothenburg Energi regarding the finished landfill called Arendal at Torviken if they would be interested to install solar cells, but the location was not seen to be optimal according to them. From the author's point of view this is interesting as this shows that there has been some dialogue with other companies regarding solar cells and indicates that Renova would be willing to collaborate to reach a common goal.

Around the area where Holmen is situated there are a lot of plans and construction taking place that means new buildings are being erected and some operations are being moved further away from the city. Discussing with Magnus he mentioned that the current plan is that Renova can keep operating from Holmen until at least 2035 and potentially even being there until 2050. With this in mind this has been used to estimate the lifetime of the buildings at Holmen. If they have been recently renovated the expected years before another renovation/removal is dictated by the number of years that the company will be allowed to operate from the same location (i.e. 2035-2020 = +15 years). For the roof capacity, it is mentioned in the table that the buildings are built according to code and should have the carrying capacity of bearing snow or wind for the Gothenburg climate. Magnus mentioned that if the next step of the project is to look in greater detail for installing solar cells it would be up to the consulting firm to calculate the carrying capacity of each roof. When it came to the roof angle, the usual technical term that I understood from having the meeting with Magnus is that the angle of a roof is portraited by giving a horizontal length and a vertical height. Basically, this means that a right-angle triangle is formed, and the angle can be calculated accordingly. For the sections with 3° in the table this was given as 10 metres and 0.5 metres elevation, and for 9°, 10 metres with 1.5 metre elevation. Additionally, the design of the roof for the two largest buildings at Holmen (H8-H11 & H18-H21) have a design that the author personally would call "W" shaped whilst roof H12 has a more traditional design of a simple right angle-triangle. Figure 23, shows a cross-sectional representation of the roofs whose angle is shown in Table 11 above.

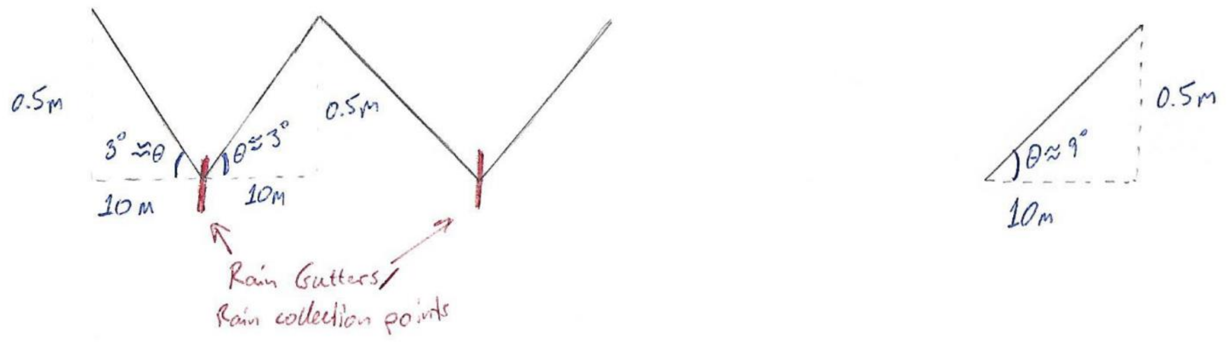


Figure 23: Cross-sectional views of roof design at Holmen (H8-H11 & H18-H21 (left) H12 (right)). The red lines show how the water runs off from the roof (the rain gutters). It should also be pointed out that the cross-sectional views are not drawn to scale, they are instead exaggerated to help illustrate the angles and lengths.

After having a short discussion with Magnus, the best or maybe most optimal locations in the sense of continuous rooftop areas available have already been visited by Camilla Svensson and the author on the fieldtrip. For clarity the optimal locations besides Holmen, could be Rödingen that also has a very large continuous rooftop with a low inclination and Marieholm that has some rooftop areas that don't have the risk of having shadows cast from other buildings. Magnus mentioned that for example Rödingen has a 7000 m² rooftop that was newly renovated. Finally, Marieholm's roofs are older, from 2001 but Magnus mentioned if they are needed or seen as being good applicants for solar PV's, they could be renovated in conjunction with new solar cells being installed. On a side note, during the discussion Magnus mentioned that the contractor that did the renovations at Holmen this year mentioned that the government is planning to make the rules for installing solar cells to roofs stricter. The government is planning to do so, as it has been noticed that the mountings between the roof and solar cells have not been strong enough to withstand the elements.

From the meeting with Magnus Lundström table 11 was created. Tacking the values and the comments from table 11; table 12 is presented below. Table 12 shows how the theoretical available rooftop areas at Holmen for solar PV's are combined with the comments from the meeting to give a more realistic value for areas applicable for solar PV.

Table 12: Changes made to the theoretical table for available rooftop areas at Holmen for solar PV according to interpretation from meeting with Magnus Lundström.

Section	Length [m]	Width [m]	Approx. available [%]	Area for PV [m^2]
H1	87.35	6.4	0	0
H2	90.35	5.65	0	0
H3	86.55	5	0	0
H4	7.8	7.8	0	0
H5	27.8	6.25	0	0
H6	42	11.5	85	410.55
H7	42	11.5	90	434.7
H8	62	10	95	589
H9	62	15	95	883.5
H10	62	15	95	883.5
H11	62	10	95	589
H12	10	22	90	198
H13	55	12	90	594
H14	55	12	90	594
H15	13	22	90	257.4
H16	54	12	0	0
H17	54	12	0	0
H18	68	10	95	646
H19	68	15	95	969
H20	68	15.5	95	1001.3
H21	68	10	95	646
H22	23	5.5	90	113.85
H23	35	9	90	283.5
H24	13	7	60	54.6
H25	13	7	75	68.25
Sum				9216.15

For areas H1-H5 and H16-H17 an area available for solar PV was given a 0 percent possibility due to the comments from the meeting with Magnus. For the areas that were not discussed but are still represented (i.e. H6,H7,H15,H22-H25) an interpretation is made by the author as the comments made during the meeting were seen as not totally eliminating these areas but merely that they are not large enough or would probably not have the same cost of installation. This is said as it is assumed that large continuous areas would be cheaper per square metre in comparison to many small roofs. Additionally, the aggregated sum of rooftops for H8-H11 and H18-H21 do not add up to the 7000 m² that Magnus mentioned during the meeting (difference of around 800 m^2). With the deviation of the two buildings and the possibility that the images used from Google Maps were not up to date, the lowest value of the two will be used in the calculation of expected electrical energy (i.e. around 6200 instead of 7000 m^2). This is the case as the exact lengths and widths were not discussed during the meeting making it more difficult to divide a large roof into four sections as it was not discussed how even the distribution is. In doing so, it is more comfortably said that with this assumption the calculated rooftops for solar PV at Holmen could be closer to the actual value. Table 13 shows table 12 filled in with the expected electrical output from the buildings at Holmen.

Table 13: Possible areas for rooftop mounted solar cells at Holmen and expected electrical output.

Section	Length [m]	Width [m]	Approx. Available [%]	Area for PV [m^2]	Yearly irradiation energy [kWh/m²/yr]	Electrical output [kWh/yr]
H1	87.35	6.4	0	0	975	0
H2	90.35	5.65	0	0	1100	0
H3	86.55	5	0	0	975	0
H4	7.8	7.8	0	0	975	0
H5	27.8	6.25	0	0	975	0
H6	42	11.5	85	410.55	975	72052
H7	42	11.5	90	434.7	1100	86071
H8	62	10	95	589	1100	116622
H9	62	15	95	883.5	975	155054
H10	62	15	95	883.5	1100	174933
H11	62	10	95	589	975	103370
H12	10	22	90	198	975	34749
H13	55	12	90	594	975	104247
H14	55	12	90	594	1100	117612
H15	13	22	90	257.4	975	45174
H16	54	12	0	0	975	0
H17	54	12	0	0	1100	0
H18	68	10	95	646	1100	127908
H19	68	15	95	969	975	170060
H20	68	15.5	95	1001.3	1100	198257
H21	68	10	95	646	975	113373
H22	23	5.5	90	113.85	975	19981
H23	35	9	90	283.5	1100	56133
H24	13	7	60	54.6	975	9582
H25	13	7	75	68.25	1100	13514
Sum				9216.15		1718690

In short from table 13 it can be seen that with around 9200 m^2 of solar cells around 1.72 GWh of electrical energy can be expected from the solar cells. It is very good that so much electrical energy can be expected from Holmen as this is also the location where most of the vehicles are found. Using the derived energy needed to produce and compress the hydrogen of 57.9 kWh/kg and a daily demand of 28 kg of hydrogen and an assumption of 365 days in use the yearly energy demand can be calculated. With the previously stated parameters the expected electrical demand of 0.6 GWh would be needed (57.9 kWh/kg x 28 kg/day x 365 day/year = 591738 kWh ÷ 10^6 = 0.59 GWh). An electrical supply of 1.72 GWh is almost twice the expected yearly demand which could potentially mean that as a first step only these buildings would be needed to be considered to provide enough energy to meet the hydrogen trucks demand. However, in the interest of seeing the energy available from Renova itself, the waste to energy plant (Sävenäs) will be analysed in the following section.

4.1.3 Energy recovery potential from waste to energy plant (Sävenäs)

The waste-to-energy plant at Sävenäs is a facility that Renova owns and uses to incinerate waste and produce heat and electricity. On average around 300 trucks deliver waste to the Sävenäs plant on a daily basis, in order to fuel four incineration grated-fired furnaces. Approximately, 60% of the electricity that is produced out of all of the waste that is received and processed at the plant can be labelled as biofuel based. In short, this means that 40% of the CO_2 emissions get taxed with an incineration tax that was recently introduced. The flue gas cleaning system is comprised of multiple stages of both wet and dry cleaning, which results in flue gas emission levels being lower than the European Union's requirements. Additionally, it can be summarised that for every ton of waste that is combusted today at Sävenäs, around 3.3 MWh of energy both in electricity and district heat is recovered (Renova, n.d.-b).

To help the reader get a better view and understanding of the following text, a simple representation of the energy transfer for the district heating loop through the Sävenäs plant is shown below in figure 24.

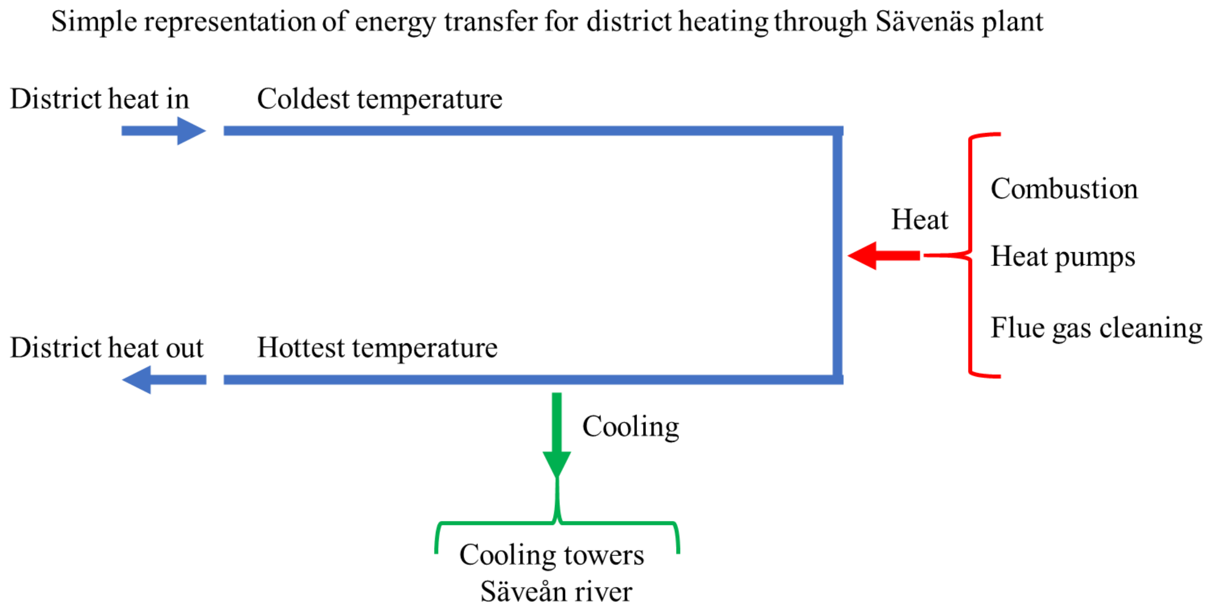


Figure 24: Schematic overview of the Sävenäs plant were the district heating loop passes through the plant and successively increases its temperature.

In short, what is shown in figure 24 is that in a simplistic way everything has to do with heat transfer, the blue line represents what can take up energy (district heating loop) while the red arrow represents what is providing the heat, to heat up the system. Additionally, if the customer, Gothenburg Energi, requires less heat to be supplied by the Sävenäs plant, then the green arrow indicates what is used to partially cool the district heating loop. Primarily the main part of the cooling is carried out by the cooling towers and the Säveån river is used less often and with lower cooling amounts/capacities.

When it comes to transferring energy from the plant's various processes to increase the temperature of the incoming district heating there are not a lot of changes that can be made to make it more efficient at a reasonable cost. Also, the demand for district heating is not the same all year round. During the colder parts of the year almost all the heat that Sävenäs can produce is taken up by the district heating line/network. During the warmer parts of the year demand for district heat drops and is at times lower than what Sävenäs can deliver. Had this been any other power plant the next step would be to reduce the thermal output of the plant. However, as the main goal of the plant is to take care of garbage (incinerate and reduce volume), its furnaces are intended to run at maximum capacity year-round. The energy up-take and utilization, either as steam through a turbine generating electricity or heating the district heating network is a positive by-product that has been developed throughout the years (hence the name waste-to-energy). The type of turbine that is used at Sävenäs is known as a backpressure turbine while another common type of steam turbine is the condensing turbine. In short, the difference between the two types is that for a backpressure turbine the media (steam/ wet steam etc) exits at a higher pressure, while a condensing turbine allows for a lower pressure to be achieved before the media exits the turbine. This in turn means heat with a higher value comes out of the backpressure turbine which in this case is used to heat the district heating network (for example through a condensing heat exchanger). Figure 25 below, illustrates in more detail how the district heating line/loop works with the Sävenäs plant.

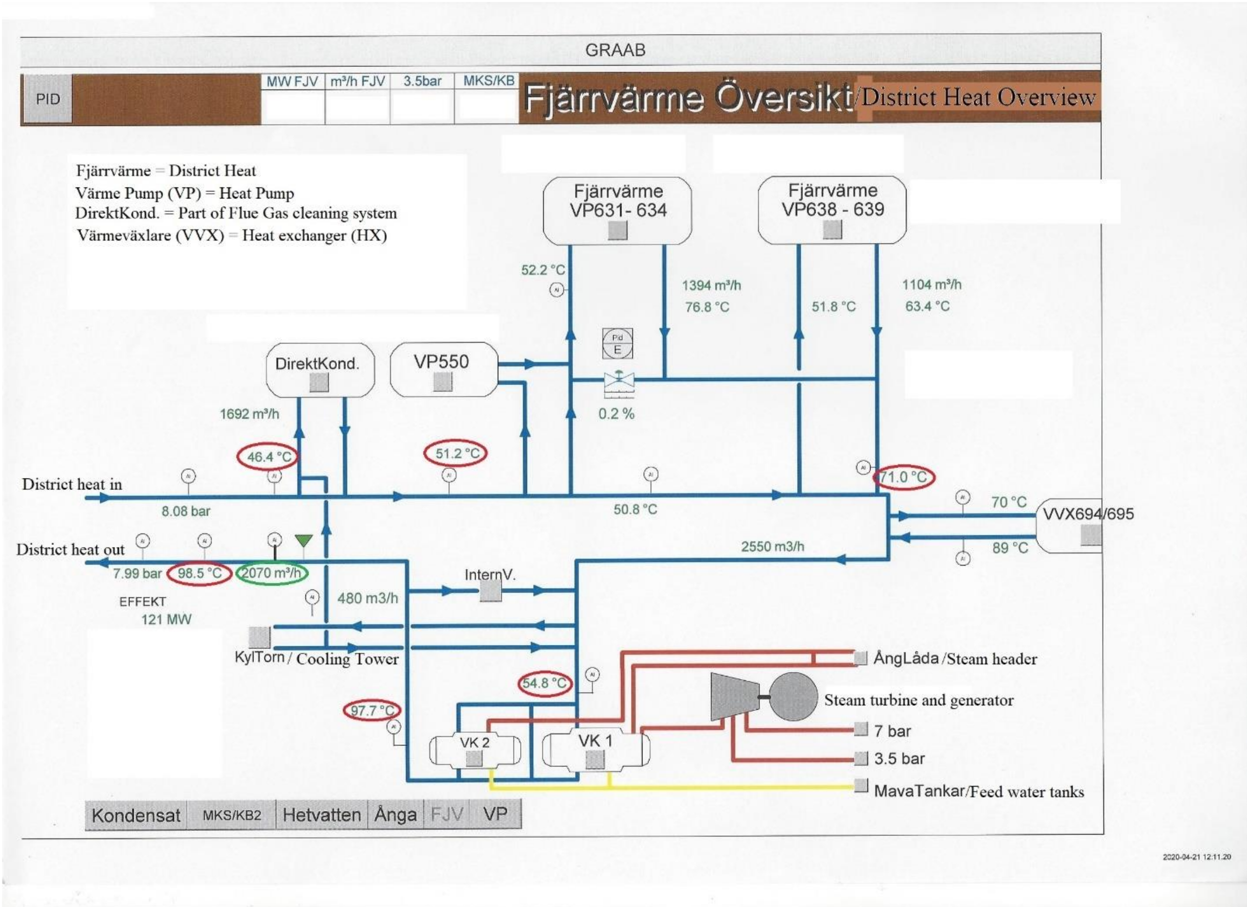


Figure 25: District heating overview across the Sävenäs plant on a hot day with the cooling towers just being turned on (Copyright given by personal correspondence with Renova). Blue lines represent district heating flow, red lines represent steam and yellow lines represent condensate (condensed steam = water). The district heating loop passes through the flue gas cleaning system (Direkt.Kond) were heat is exchanged from the flue gas cleaning system to the district heating loop. More heat is added to the district heating loop by the heat pumps (VP631-634 & VP638-639) whilst VP550 is used internally at the plant. VVX694/695 are heat exchangers that are also part of the flue gas cleaning system but at a different location and temperatures. The cooling towers cool the district heating loop if needed. VK1 and/or VK2 condense the steam from the steam turbine or directly from the steam header and simultaneously transfer heat to the district heating loop, also this is the last part of the heating process. Säveån river cooling does not directly cool the district heating loop hence not being shown in this view.

In figure 25 above, the red circles illustrate the usual case where there is a gradual increase in temperature of the district heating loop from the low temperature incoming and the hotter outgoing district heating fluid. However, on the day (2020/04/21) when the screenshot was taken it was unusually hot and the control room had just been requested to cool as much as possible. This meant that until a balance is reached the temperatures in the red circles do not perfectly follow the idea of the gradual increase in district heating temperature across the plant. The temperatures in figure 25 are just an example of how successively the temperature rises. Also, the green circle in figure 25 highlight the usual flow across the plant. The other green markings represent the flow to or from a section of the plant. For example, the 480 m^3/h flow just to the right of the green circle, represents the flow from the cooling towers to the flue gas cleaning system (DirektKond). However, as the cooling towers were running the value shown exiting the plant (green circle) (2070 m^3/h) is the difference between the total flow (2550 m^3/h before VK1) and the flow going to the cooling towers (circulated internally)(480 m^3/h).

As mentioned earlier the plant can produce more heat than the district heating network needs, as was the case when the screenshot was taken. In short what happens when the demand for heat drops is that the flow of district heating through the plant also drops. As the turbine used is a backpressure turbine, reducing the district heating flow through the plant, reduces the flow though the condensing heat exchanger (called VK1 in figure 25) which in turn reduces the amount of heat taken up. This in turn reduces the electric output of the turbine and generator as the backpressure increases and less energy is transferred from the expanding steam to the turbine blades. Therefore, reducing the district heating flow through the plant also reduces the electrical output. With this effect (reduction in flow) various other parts of the plant that depend on heat transfer to work properly also start to work at sub-optimal levels. A way to mitigate this issue that Sävenäs uses, is to have cooling towers that cool some of the district heating network thus allowing for more heat to be transferred from the plant to the district heating network and allowing the plant to operate as close to maximum capacity as possible. An approximation of the maximum cooling power under normal running conditions for the towers is around 65 MW. In short, the cooling towers can be described as wet cooling towers, were water is sprayed onto a large surface area allowing better heat transfer, evaporating, and removing heat from the district heating loop. To transfer enough energy to the district heating network is also vital for the flue gas cleaning system. The more energy that gets transferred to the district heating network allows more substances to be precipitated from the flue gas when it is being cleaned (especially for the wet scrubbing of the flue gas). Additionally, parts of the analysis have been done with the help of Malin Bruhn who is a process engineer at Renova.

There have been certain times when the cooling capacity of the cooling towers have not been enough or the returning district heating network temperature to Sävenäs has been too high. When there is inadequate cooling for certain equipment, the adjacent river called Säveån is used were river water is heat exchanged and used to cool said equipment. The extent to how much water can be extracted, used and returned to the river is dictated by an environmental ruling that sets requirements to the Sävenäs plant. The requirements state that at certain flows of the river (in m^3/s) there is a limit to how much water can be extracted, consumed, returned and a maximum temperature difference between incoming and outgoing temperatures (ΔT). Table 14 below, illustrates the limits set by the environmental ruling for how much Sävenäs can extract, consume, and return water from and to Säveån river.

Table 14: Limits set by environmental rulings for Säveån river and the Sävenäs plant.

Säveån Flow [m³/s]	Max. extraction [m³/h]	Returned [m³/h]	Consumed [m³/h]	Max. ΔT [°C]
>4	900	750	150	15
<4	500	400	100	15
<2	-	0	-	-

From table 14 it can be seen that there are three flow boundaries set for the Säveån river (above and below 4 m^3/s and below 2 m^3/s) and for the Sävenäs plant, limits are set accordingly where the lower the river flows the less water that is available for the plant. When it comes to the lowest Säveån flow (below 2 m^3/s) in table 14 it can be seen that there is no direct restriction on maximum extraction, consumption and temperature difference but only on the return flow which is set to 0 m^3/h. The values for maximum extraction and consumed water volume are not restricted as the way the water is consumed at the plant is by filling a holding tank that feeds the plant equipment (such as fire pumps). There is no maximum allowable temperature difference because there is a restriction that no water can be returned to the river when it is flowing below 2 m^3/s.

As the plant is intended to always run at maximum capacity while demand is sometimes lower in the summer, a possibility of trying to utilize this low grade heat (too low to drive a steam generator) rather than cooling it to ambient temperature would be a win-win situation (both environmentally and company wise). Ideally, it would be great if there was a method/technology that can utilize heat at these temperatures and produce electricity, as electricity can always be utilized and sold to the electricity grid or even used internally. A technology that could be able to help realise this idea and help tackle to a degree this issue is equipment utilizing the Organic Rankine Cycle (ORC) principle. In short, the difference between a normal Rankine cycle and the ORC is that an organic medium at lower pressures (usually below atmospheric pressure) is used by evaporating, driving/expanding over a turbine and then condensing back to a liquid rather than using other media (for example steam and a steam turbine) at higher pressures than atmospheric pressure. The way that the ORC system is thought to help the plant is that in a way it creates an artificial demand for heat, in this case district heat and the output will be electricity. In theory, in doing so it helps take up some of the energy from the district heating network, allowing for higher flows through the plant and in turn helping the other parts of the plant work as optimally as possible. In the review from M. Villarini et al. an ORC setup is explained, were the cycle consists of a pump supplying the organic fluid to the evaporator, were it gets heated and vaporised from the external heat source. Additionally, the vapour now having a higher pressure, exits the evaporator, and enters for example a turbine where it expands and drives the turbine (producing power). After having expanded through the turbine the media now has a lower pressure and exits the turbine and enters the condenser where it cools down (from an external cooling source), becomes a liquid (condenses) and can be pumped again by the pump to the evaporator, creating a new cycle (Villarini et al., 2014).

In a review from F. Vélez et al. it points out that some of the advantages of ORC technologies are low staffing expenses, low maintenance expenses, remote/automatic, continuous working, low pressures (compared to steam cycles), ease of starting up, reliability, even at partial loads can have high efficiencies and as the media is not water, it does not face any corrosion issues associated with water (Vélez et al., 2012). This is also supported in an ORC review by S. Lecompte et al. were the ORC benefits from working with low temperatures and still producing electricity, low maintenance, low pressure operations and autonomous/remote operation (Lecompte et al., 2015). Furthermore, in the review from F. Vélez et al. it mentions that as the ORC units can work with large power ranges and diversity of temperatures it would allow multiple units in cascade/series applications. What is meant by cascade applications is that the exit stream from one of the ORC units would still be in the operating range for another ORC unit, this could increase the overall efficiency of the plant (Vélez et al., 2012). In the same review, an ORC unit connected to a solid oxide fuel cell with the sole aim of producing electricity resulted in an efficiency of around 46%, while another configuration that tried to utilise some of the heating (cogeneration) resulted in around 71% efficiency (Vélez et al., 2012).

Additionally, it was identified that the bottle neck of the Sävenäs plant when it comes to allowing the plant to work optimally is the cold side (being able to cool the plant). If there is not enough energy capacity available in the district heating loop itself (either too high return temperature or low flow rate or combination of both) to help transfer some of the energy from the various parts of the plant, the only alternatives are the cooling towers, and a combination of Säveån river cooling and reduction of output from the plant. To be able to analyse and identify a possible position of connecting such a unit (ORC), some data was needed from Sävenäs. Hourly averages for 2019 were provided for various sensors across the Sävenäs plant. Figure 26 below, illustrates the average hourly flow of the Säveån river for 2019.

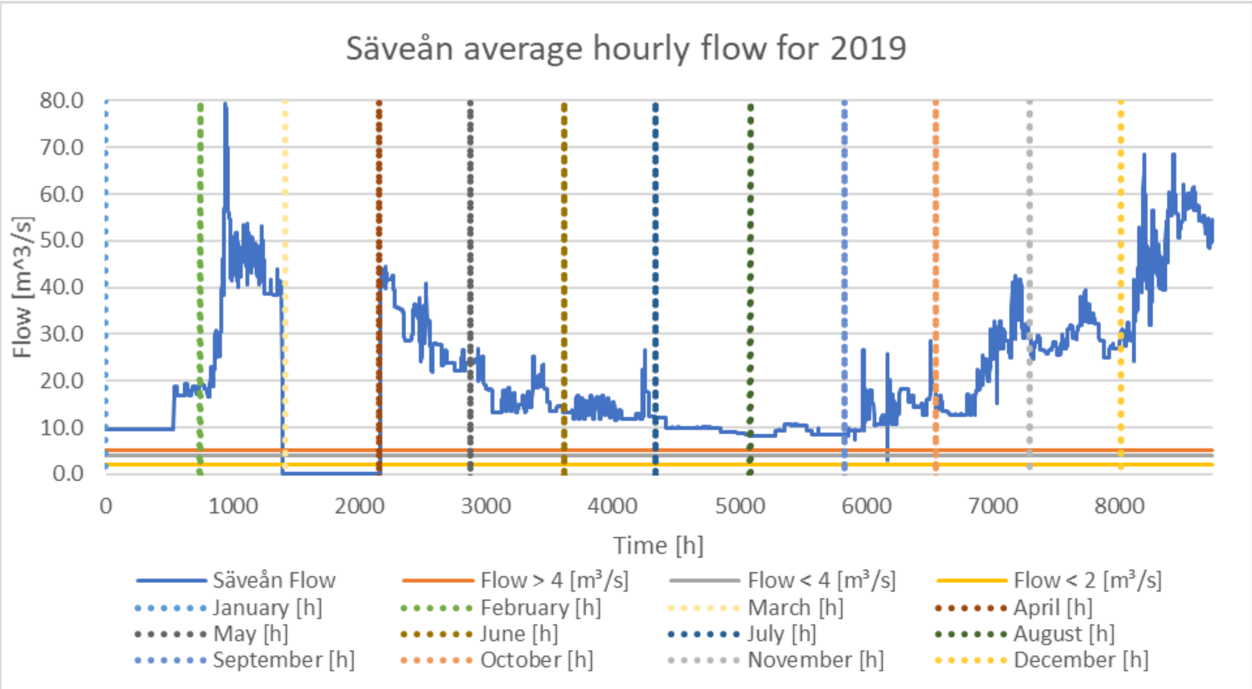


Figure 26: Hourly average flow of Säveån river for 2019.

To begin with, in figure 26 besides the hourly average which is shown in blue, for ease of comparison the environmental ruling limitations on the flow of the river were also plotted in the same figure, along with the boundaries for every month. Additionally, it should be pointed out that the range of data that was provided was from the 1st of January 2019 at midnight (00:00) until the 30th of December 2019 at 23:00, so when it is mentioned that the data spans for the hours of 2019 instead of 8760 hours, 8736 hours are plotted and analysed. Even though 24 hours (for the 31st of December 2019) were not included, it is felt that the remainder of the data are still representative of the year 2019.

In figure 26 a drastic dip in the apparent flow of the Säveån river can be seen from around 40 m^3/s to around 0-0.1 m^3/s. This value is kept constant for around 775 hours (around 32 days) i.e. between March and April boundaries. It was explained that the sensor was broken for that time period (from 2019/02/28 at 01:00 until 2019/04/01 at 09:00). However, discussing with Malin Bruhn a guesstimate of 25-40 m^3/s could have been the flow during that time. This was derived by looking at the curve in figure 26 and a couple of hours before the sensor stopped measuring and a couple of hours after it was back, the flow was around 40 m^3/s. The reason a minimum was set to 25 m^3/s was the values for the hours between 1000 and 1200 in figure 26 (between February and March), the highest flow was 55 m^3/s and lowest 40 m^3/s. Taking this into consideration a drop of 15 m^3/s (55-40 = 15) could be conservatively expected. The flow at the time of cut-off was around 40 m^3/s taking the 15 m^3/s drop into consideration, a conservative minimum flow for the period not recorded can be assumed to be 25 m^3/s (40-15 = 25). Furthermore, as the flow during that time was adequately above the environmental rulings, this did not affect the plant and how much water it can take from the Säveån river. Additionally, around 6500 hours (between September and October) (hour 6178 to be specific date: 2019/09/15 at 10:00) a sharp drop is also observed, but still being above the 2 m^3/s environmental ruling limitation. As this is only for one hour and the hours prior and after are at least above 10 m^3/s this is seen as being erroneous data and a small issue was experienced by the sensor or a short service was done to the sensor. Additionally, this is a perfect example of how data received from reality can affect an analysis or the extra steps needed to justify the data plotted. In theory knowing some of the parameters a graph can be plotted but nonstop, continuous 24/7 recording in reality does not always work smoothly. A way that this could have been avoided or if it is critical to have continuous monitoring, at least two sensors could measure the same source and if there are any anomalies with one sensor hopefully the other one would still be active and recording. Overall, from the plotted flow of the Säveån river for 2019 it can be said with confidence that for most of the year the Sävenäs plant could extract, consume and return water at the maximum allowable rate according to the environmental ruling of 900, 150 and 750 m^3/h with a maximum ΔT of 15°C respectively.

Figure 27 below illustrates the district heating demand met/delivered from the Sävenäs plant (shown in orange), the amount of cooling from the cooling towers (shown in blue), the Säveån river (shown in red) and a sharp drop due to the total stop (shown with the arrow). (Note: the black circle in the figure illustrates approximately the close up shown in figure 29).

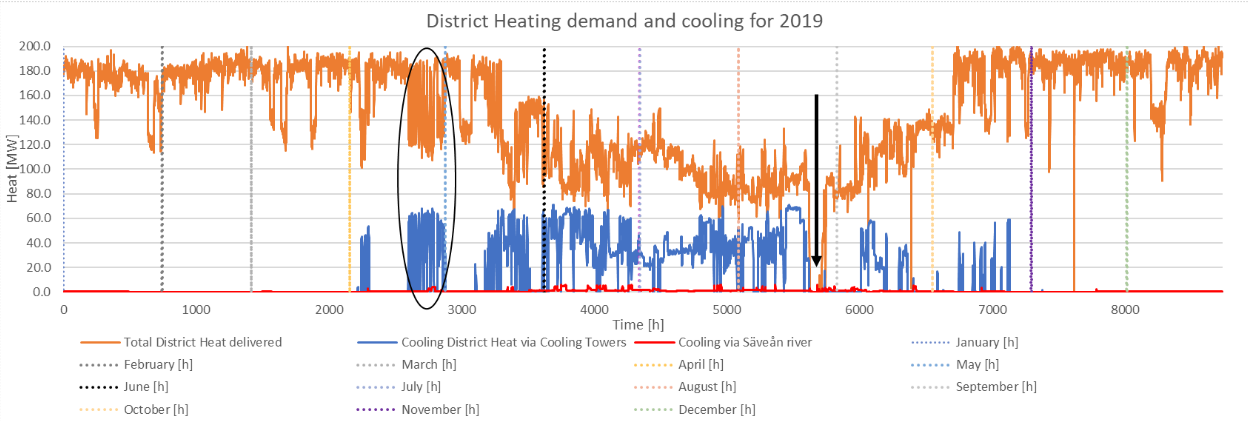


Figure 27: District heating demand and cooling from the cooling towers and the Säveån river for 2019.

From figure 27, it can be seen that the ratio or amount of heat that is delivered is greater than the amount that gets cooled by the cooling towers and the Säveån river. Additionally, it can be seen that most of the cooling takes place during the summer period or at least the warmer part of the year. This is in line with what was stated earlier that as demand falls during the summer period the plant needs to cool to meet the customer's demand and also allow it to operate. Additionally, around the 5700 hour mark (illustrated by the arrow in figure 27) a clear and sharp dip can be seen for all three measurement points. It was pointed out that during a weekend around the end of August the plant was fully stopped were maintenance was done. This is done to allow work to take place that otherwise cannot be done during the time the plant is up and running, for example electrical work at some places which require that the electricity supply is completely shut off. Additionally, such a complete stop usually happens every third year and there is a possibility of a total stop happening every second year from now on. Having the total stop in the data made it somewhat difficult to definitely say what the lower limit usually is for the amount of delivered district heating but around 60MW can be seen in figure 27 at times when the plant is operating normally. It was also mentioned that as this phenomenon of demand dropping during the summer is a recurring result, most major plant work is planned during this period. For example, it was pointed out that not all four furnaces are up and running at the same time for various hours of the summer. The maximum amount of delivered district heating during the year 2019 topped 200 MW. To help with the analysis of the cooling towers and the Säveån river cooling for 2019 a closer look at just these two parameters have been plotted in figure 28 and figure 30.

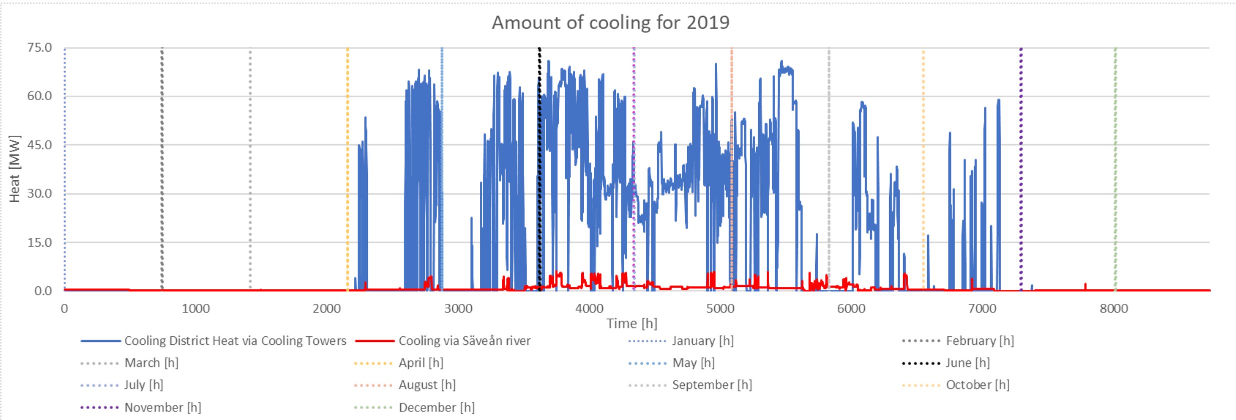


Figure 28: Amount of cooling from the cooling towers and the Säveån river for 2019.

From figure 28 it can be seen that the cooling towers are primarily run below 65 MW as mentioned earlier but at times they peak up to 71 MW. It was explained that for normal running conditions the maximum amount of cooling from the cooling towers is around 65 MW and only for short periods of time do they work higher than 65 MW. Additionally, to help the reader get an understanding for the frequency and duration of the values (how often they change and by how much) a small section of 510 hours (end of February to beginning of April) of 2019 (black marking in figure 27) is shown in figure 29.

Figure 29: Snip of heating and cooling values for hours 2490-3000 for 2019.

What can be seen more clearly in figure 29 than from the other figures due to the large number of data points is that the cooling towers fluctuate quite rapidly in both amount of cooled district heat and duration. Furthermore, it can be seen that when the cooling towers are ramped up the amount of delivered district heat decreases by the same amount (almost like the image is mirrored), and this trend is followed throughout the figure. This is interesting as this shows how varied the demand can be from time to time and from personal experience the control of the towers is manually adjusted from the control room to meet the demand of the customer. It was pointed out that in this the case as demand for heat during the night hours drops and when people wake up in the mornings demand increases again. In short, it can be said that demand follows human habits. Figure 30 below, shows the Säveån river cooling for year 2019 and the maximum available cooling from the river according to its measured flow for that hour.

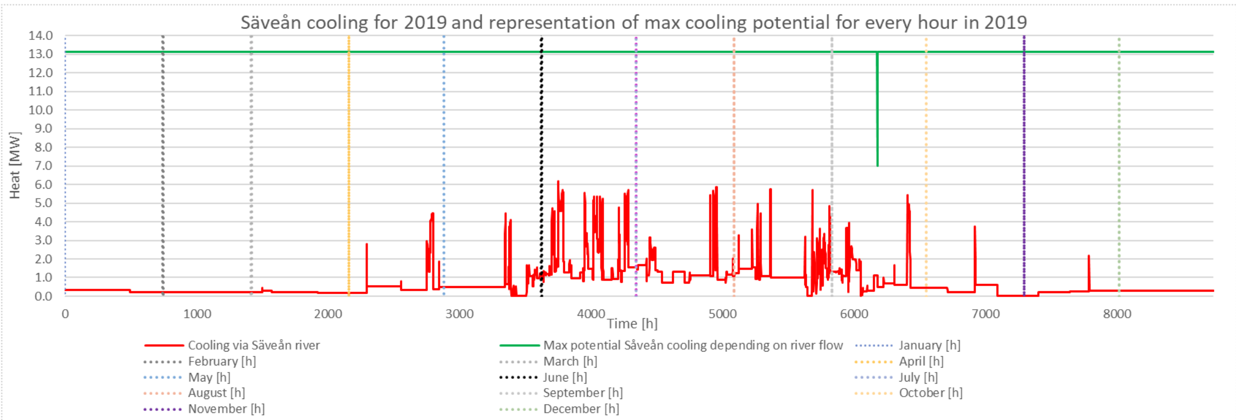


Figure 30: Säveån cooling for 2019 along with the theoretical available cooling from the river according to the flow for every hour.

From figure 30 the same sporadic usage of the Säveån river for cooling is also seen as for the cooling towers, but with a much lower amount of cooling used and available. The green line in figure 30 represents the available theoretical maximum cooling from the river according to its measured flow, return flow to the river and maximum ΔT restrictions from the environmental ruling. The Säveån river flow was above 4 m^3/s most of the year except for 15^{th} of September at 10 in the morning. Conservatively, if the assumption mentioned earlier that someone checked on the sensor at hour 6178 or it actually recorded a flow of 3.1 m^3/s, then the theoretical amount of cooling was around 7 MW. At the same hour as the flow in the river was around 3.1 m^3/s the river was also used to cool 1.1 MW. This happens to also coincide with the least allowable cooling left from the river (i.e. the difference between maximum cooling and actual cooling demand was the smallest for 2019) at around 5.9 MW. With this value for cooling available from the river, this would be the minimum available cooling for the ORC to use (cold side). So, a potential 5.9 MW or less of cooling would allow the ORC to run without any restrictions on the cooling side. The maximum cooling available from the Säveån river was around 12.8MW as the sensor never actually reached 0.0 MW for the Säveån cooling. The following paragraph explains how the approximate 13 MW and 7 MW of theoretical cooling from the Säveån river were calculated.

Using the maximum allowable returned values and maximum ΔT from table 14 and heat capacity of water (Cp 4.2 J/(g K)) the amount of cooling available from the river is calculated to be around 13 MW and 7 MW at flows above and below 4 m^3/s respectively. These values were calculated using the heat energy equation,

$$Q = \dot{m} \times C_p \times \Delta T \qquad (3)$$

where Q is the heat, $\dot{m}$ the mass flow and ΔT the temperature difference, in this case 15 K.

It was pointed out that the Säveån river was used this much in 2019 as all heat pumps were not fully operational during 2019. It was explained that having more heat pumps allows for more cooling to reach the critical parts of the plant. With that said, the need for cooling from the Säveån river might drop for the following years. This would allow for more hours to run of the ORC system, increasing its full load hours (FLH) meaning it gets utilised more in a given year. Figure 31 below, illustrates the hourly average incoming temperatures to the Sävenäs plant for 2019.

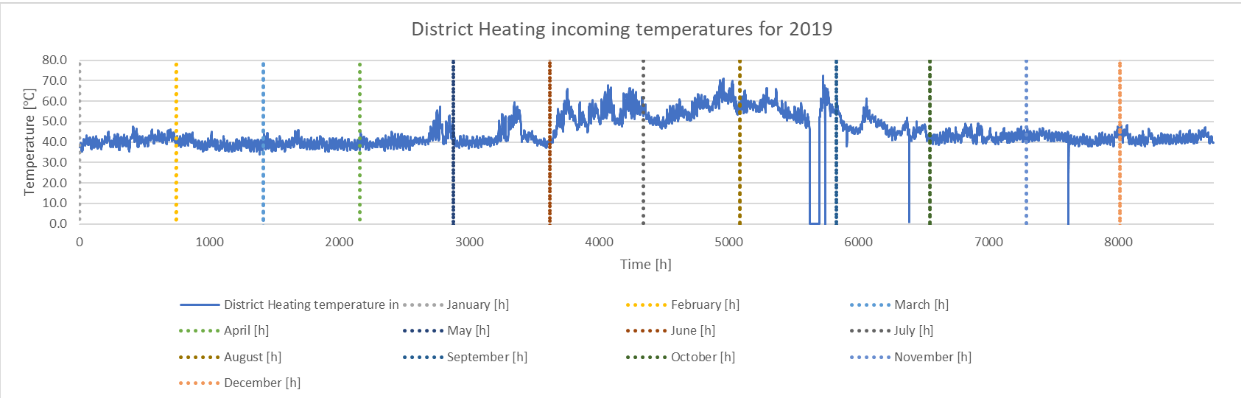


Figure 31: District heating incoming temperatures to the Sävenäs plant for 2019.

From figure 31 it can be seen that during the cooler parts of the year the incoming temperature for the district heating is around 40°C. Whilst during the summer period the incoming temperature starts to rise, with the highest recorded incoming temperature for 2019 being 72.5°C (27^{th} of August at 18:00). As mentioned earlier if the incoming temperature rises too much some parts of the plant run too hot and the Säveån river is used to cool the loops that would usually be cooled by the district heating line but as the district heating line gets too hot it stops providing the necessary cooling to these loops which are seen as critical parts to allowing the plant to function properly. This is also seen as the spikes in temperature in figure 31 coincide with most of the times that the Säveån cooling is used in figure 30. Figure 32 below, illustrates the temperatures of the district heating loop before and after the steam condensing heat exchanger VK1.

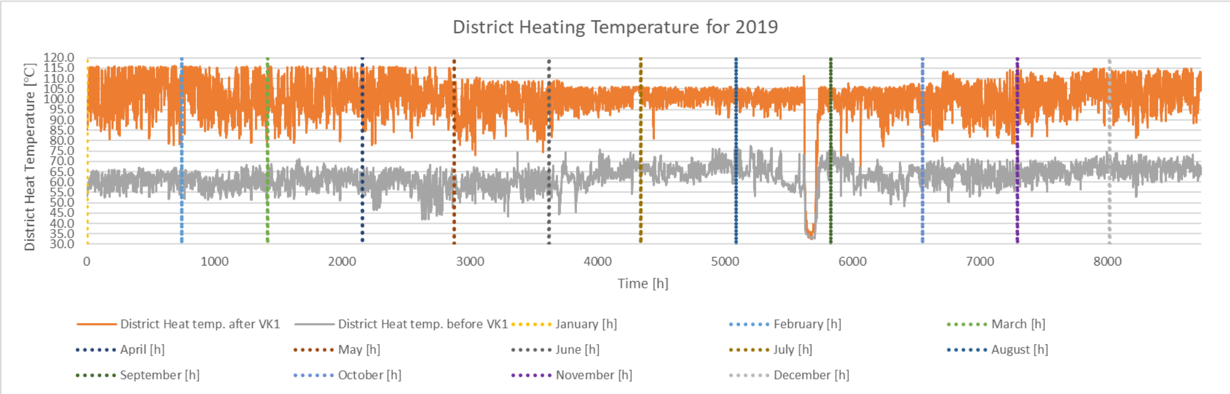


Figure 32: District heating temperatures before and after VK1 for 2019.

It was explained that the customer, Gothenburg Energi, usually wants the outgoing district heat temperature from Sävenäs to be around 95°C during the summer period, but it usually is closer to 100°C. Furthermore, during the winter period the outgoing district heating temperatures are very dependent on the outside temperatures. When it gets very cold outside the outgoing temperature from the Sävenäs plant is usually around 110°C-115°C. If the temperature reaches close to 120°C, Gothenburg Energi, must increase the flow to drop the temperature as the district heating network is rated for max 120°C. This can also be seen in figure 32 were higher temperatures are seen in the colder parts of the year with a maximum for 2019 being 116°C after VK1, while in the summer period the temperature drops closer to around 100°C - 105°C.

Even though the temperatures shown in figure 32 were measured after VK1 and are thus not exactly the same as the outgoing temperature from the plant the two temperatures always are very close to each other with a deviation of less than 2°C. This can be said as this is the last step of the plant that transfers heat to the district heating loop before exiting the plant. Due to the total stop that took place in August a reasonable/acceptable momentary minimum temperature from VK1 can be estimated to be around 80-85°C. During the total stop there was a larger temperature difference between the outgoing temperature sensor from the plant and VK1, where one showed 0°C and VK1 32°C. This was probably because the sensor could have been disconnected for the outgoing temperature from the plant while for VK1 as it is indoors it was probably measuring the room temperature. This was the only drastic deviation between the two sensors. When it comes to the temperatures before VK1 a maximum temperature of 77.5°C was recorded for 2019 while an approximate lowest temperature was around 65°C (not exact due to the total stop). Figure 33 below, illustrates the measured hourly temperature of the Säveån river for year 2019.

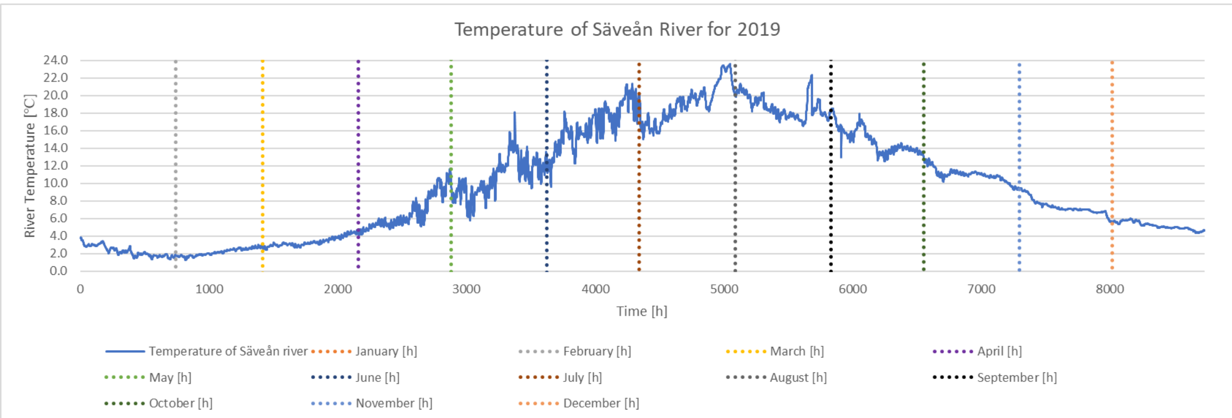


Figure 33: Measured temperature of the Säveån river for 2019.

From figure 33 it can be seen that the lowest temperature of the Säveån river for 2019 was around 1.3°C, during the winter period, and highest during the summer period with temperatures up to around 23.6°C.

With these recorded temperatures a sensible hypothesis could be that the cold side of the ORC could vary with around 22°C. This means that it could potentially affect the efficiency of the system as the temperature difference between the hot and cold side would decrease and using the heat energy equation trying to maintain the same energy with a decreasing ΔT would result in an increase in flow, to maintain balance, which would mean more work done from the pumps with rising temperatures (within the ORC loop itself, as the cooling from Säveån is always restricted by the maximum allowable ΔT of 15°C) . Figure 34 below, shows the measured flow of the district heating fluid that is leaving the Sävenäs plant.

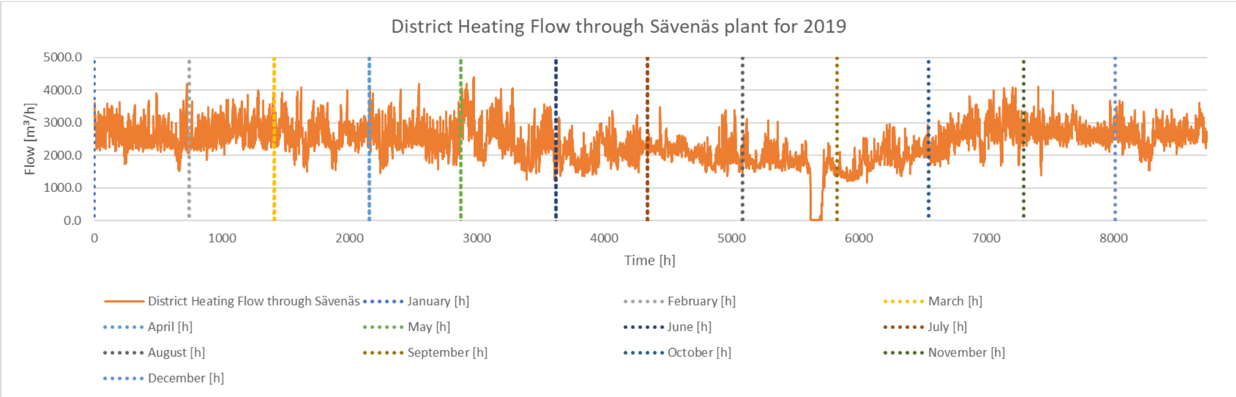


Figure 34: District heating flow that is measured leaving the Sävenäs plant.

It can be pointed out that the outgoing district heating fluid leaving the plant does not represent the total fluid that is circulating in the plant, but using these flows and temperatures shown in the previous figures of the returning temperature of the fluid and outgoing temperatures; then the delivered district heating amount could be calculated with the graphs provided in this report. Additionally, from figure 25 it can be seen that the cooling towers take some of the flow from the district heating loop and send it back to the beginning or return it back to the loop just before VK1. This means the recorded outgoing flow from the plant is also the same amount that passed through VK1. As can be seen in figure 34 the maximum flow is around 4400 m^3/h and for normal conditions excluding the total stop a minimum flow though VK1 and out of the plant is around 1500 m^3/h. Additionally, the flows vary as they do in figure 34 due to Gothenburg Energi steering the district heating pumps according to the desired temperature. Figure 35 below, illustrates the accumulated number of hours that the cooling towers operated to cool the district heating loop for 2019.

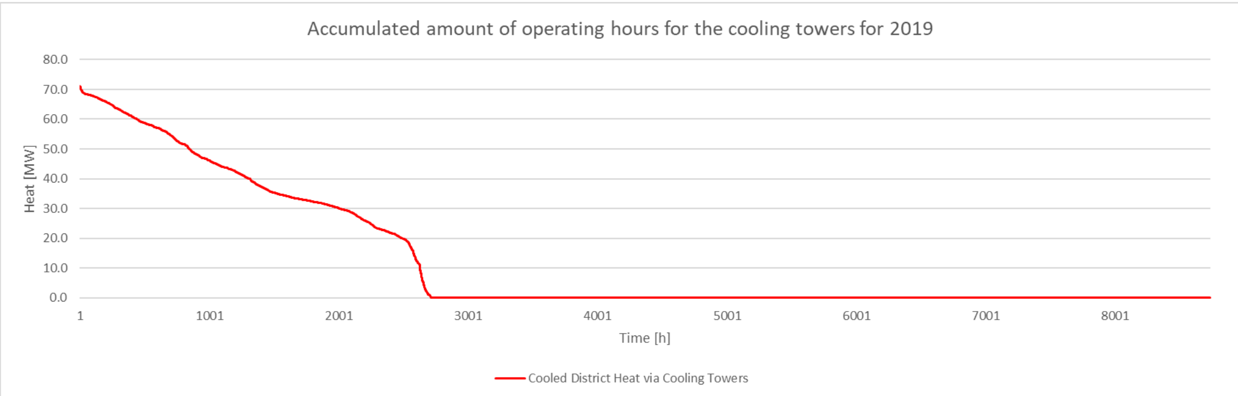


Figure 35: Accumulated operating hours for the cooling towers for 2019(Note: these are not the actual hours that the cooling towers were operated in 2019, this can be seen in Figure 28).

From figure 35, it can be seen that for most part of the year (out of the total available hours of the year) the cooling towers are not used. In total, the cooling towers were operating for 2716 hours during 2019. This means that out of 8760 hours, the cooling towers were only used a third of the time. Furthermore, the cooling towers maximum cooling capacity was fully utilised only for a couple of hundred hours. As the amount of cooling that was used in the spread sheet was on an hourly average basis, means that the total cooled energy from the cooling towers can be calculated (summing up the power for every hour). For 2019 the amount of cooling energy provided by the cooling towers were found to be 110313 MWh (or 110.3 GWh). Assuming that the plant was running at normal conditions it can be said that for most part of the year the current cooling towers can meet the cooling demand. What is not representative in the figure is how much the maximum cooling demand was, it only shows the amount that was able to be cooled from the towers.

With this section an analysis was done to try and identify the most suitable size of the ORC unit, by seeing the demand for heat and cooling, how it is provided now, at what temperatures and flows. The following section will try to calculate and suggest a possible size of the ORC unit and a location that would allow it to work with the plant rather than to work against it. Table 15 below, gives a summary of the minimum and maximum values from the figures presented in this section that could be helpful for the ORC section.

Table 15: Summary table of useful values for ORC analysis.

	Säveån river flow [m³/s]	Säveån river return allowed [m³/h]	Säveån river temp. [°C]	Cooling by cooling towers [MW]	Temp. before VK1 [°C]	Temp. after VK1 [°C]	Flow through plant/VK1 [m³/h]
Max.	79.4	750	23.6	71	77.5	116	4400
Min.	3.1	400	1.3	0	65	85	1100

4.1.3.1 Organic Rankine Cycle (ORC)

As seen from the analysis in the previous section there is plenty of heat available but limited cooling, and some suitable temperature levels for the potential use of an ORC unit in meeting the customer's demands and utilizing some of the excess energy of the plant. Two companies that produce and provide ORC units are analysed below, one is called Climeon AB and the other Againity AB.

When it comes to Climeon AB a video that was found online (YouTube, 2019a) is used to make some calculations along with the brochure found on their website (Climeon AB, n.d.-b). The reason the video is seen as being useful for the analysis is that during the presentation various examples and information that are not mentioned in the brochure were presented. To begin with an example of a possible set-up of the equipment was shown, the figure was reconstructed and presented below in figure 36.

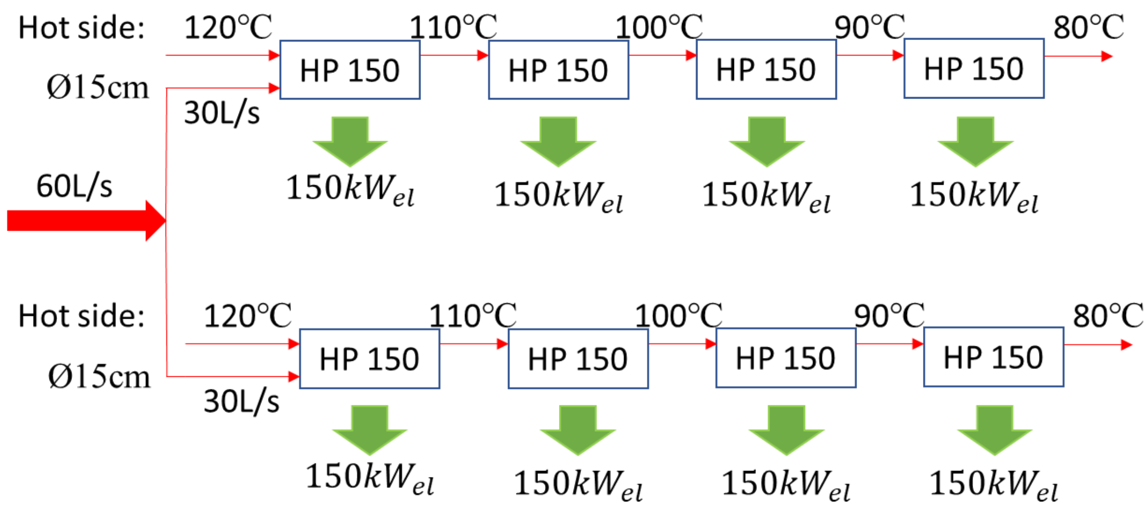


Figure 36: Reconstruction of an example of ORC machines set-up given during Climeon AB's presentation.

During the presentation a set-up of four ORC machines connected in series was first shown, then it was mentioned and shown that if the flow was doubled (from 30 L/s to 60 L/s) four more ORC machines could be connected in parallel. Figure 36 above, shows the final representation of the example given during the presentation. Additionally, in the example, it was mentioned that if a pipe of 15 cm in diameter was used with a flow of 30 L/s and an initial temperature of 120℃, then four machines could be used with a ΔT of 10℃ each, with a final exit temperature of 80℃. Additionally, it should be mentioned that the core idea of the company is to only have one size of the ORC unit and if more thermal energy is available then more units can be connected, as shown in figure 36. Each ORC unit is made to deliver 150 kW of electricity at the designed working temperatures and flows. The ORC unit from Climeon AB is called HP150. During the presentation, the size of each unit was described to be 2x2x2 metres and cost around 350 000 euros. Furthermore, it was interesting to hear that the quickest that Climeon has delivered a project from pre-study to up and running units was around 10 months for a customer in Iceland. The presenters believe that this time could become even less in the future. It is interesting as this shows how quickly a change could be made to both help meet the customer needs of Renova but also be able to utilise the excess energy. Based on the comments during the presentation, and as long as the hot side temperatures is within the boundaries of the manufacturer and the example flow, then all four units should produce 150 kW of electrical power each during use. Moving on, to help create a better picture of the possibilities and working areas of the HP150 a couple of tables summarizing the values from the brochure have been created. Table 16 below, shows data according to the manufacturer for the HP150 unit from Climeon AB along with its weight.

Table 16: Minimum and Maximum values for Hot and Cold side and weight of HP150 ORC unit according to Climeon AB brochure. Source of values: (Climeon AB, n.d.-b).

	Hot side [°C]	Hot Side Flow rate [L/s]	Cold side [°C]	Cold Side Flow rate [L/s]	Weight [Kg]
Max.	120	35	35	35	10200 (filled)
Min.	70	10	0	10	9000 (dry)

From table 16 it can be seen that the working range of the HP150 unit is quite large (70-120°C), but it is unclear how the efficiency varies with temperature, for example does it perform better at 120°C than 70°C. The possibility of efficiency deviation according to the hot side temperature was never mentioned in the presentation or brochure. Additionally, as the minimum hot side temperature is around 70°C and using a 10°C reduction in the outgoing hot side temperature as in the example from table 16 immediately eliminates some parts of the plant where the ORC unit return connection could be. For example, even if the flows are smaller from the ORC unit (compared to district heating loop), the incoming district heating loop to the Sävenäs plant would not be suitable for the return connection from the ORC as the temperatures in the summer are too high to begin with. The cold side loop boundaries for both temperature and flow luckily can be met with the Säveån river. Ideally, a connection between the two systems (ORC and district heating loop) would be where they both have the same temperature. The following tables illustrate the size of the unit along with the recommended spacings around the machine. Comparing the values from table 17 and what was mentioned in the presentation it is clear that they do not match completely.

Table 17: HP150 size according to Climeon AB brochure. Source of values: (Climeon AB, n.d.-b).

Footprint	Height [mm]	Depth [mm]	Width [mm]
Unit size	2271	3009	2085

Table 18: Recommended space around the HP150 unit from the Climeon AB brochure. Source of values: (Climeon AB, n.d.-b).

Recommended space	Above the unit [mm]	In front of unit [mm]	Behind the unit [mm]	Between units [mm]
	500	1500	691	500

From the brochure it was noted that some extra space is needed around the unit. This is probably to allow for more access points during maintenance. Additionally, it was recommended that around 500 millimetres distance should be kept between units. Taking the values from table 17 and table 18 the aggregated footprint of the HP150 is presented in table 19.

Table 19: Aggregated size of the HP150 unit.

Footprint	Height [mm]	Depth [mm]	Width [mm]
Incl. recommended space	2771	5200	2585

Overall, taking the various parameters of both the unit and area needed around it, makes it larger than presented. This is pointed out as the Sävenäs plant is quite limited in available space for new equipment. This is merely pointed out and will not be investigated further in this report but could be useful in helping choose a possible second step of the project. Taking the example given during the presentation (figure 36) and the data from the brochure a similar setup is suggested for the Sävenäs plant. The suggested setup for the Sävenäs plant using HP150 units from Climeon AB and the hot side temperatures is shown in figure 37 below.

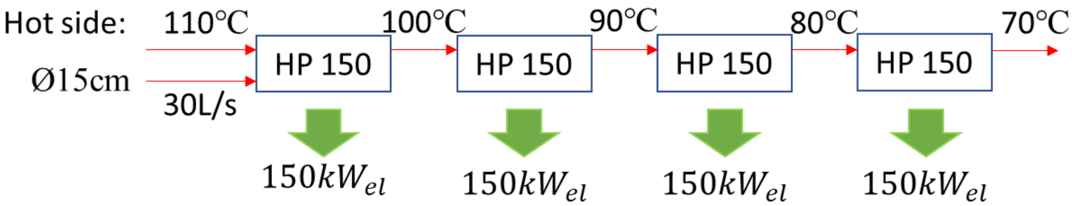


Figure 37: Approximate hot side temperatures using example template but with values for the Sävenäs plant.

The temperatures for the hot side in figure 37 might be slightly higher than figure 32 during the suggested period but as the lowest exit temperature from the ORC turbine is not specified it can be assumed that with these temperatures all four units should be able to function. This is said as the lowest exit temperature of the last ORC unit is the minimum temperature (70°C) that the brochure states (table 16). As there is no explanation to how much cooling each unit needs and at what temperature the ORC media condenses and liquifies, some assumptions are made on what conditions the ORC media would need to be cooled down to work. Figure 38 below, tries to give the reader a simple overview of the ORC system and the values by Climeon AB along with a list of assumptions that are used to fill in the blanks of the model.

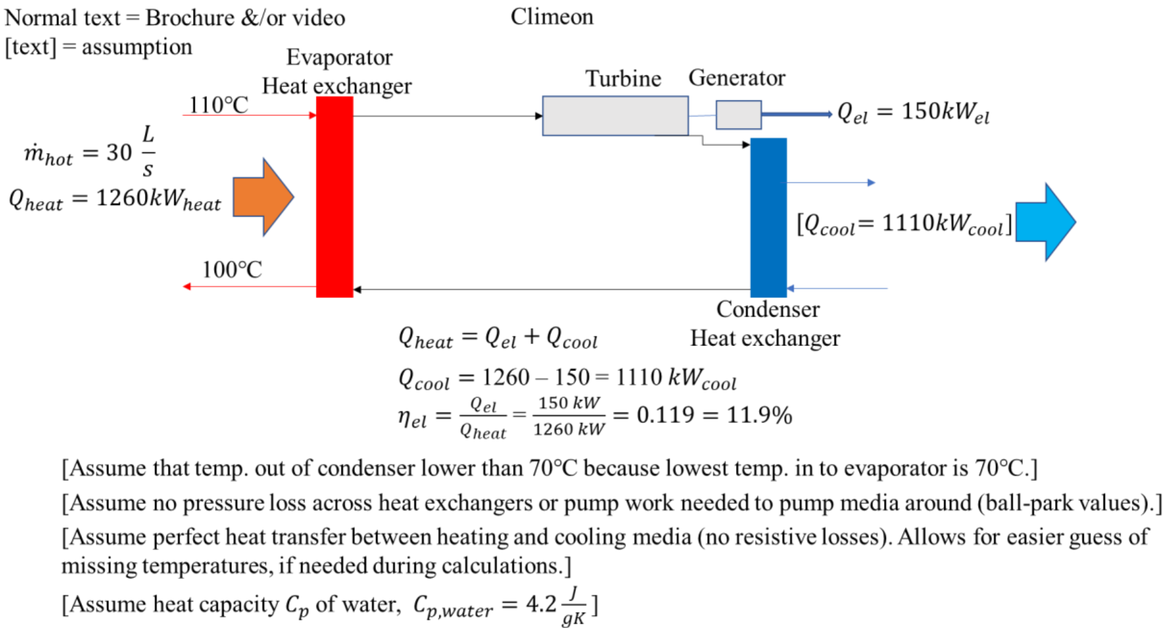


Figure 38: Simple schematic over ORC unit and values used are from Climeon AB brochure and video along with own assumptions.

As the flow through each ORC unit that is connected in series is the same along with the temperature differences (10°C) only one of the units is shown in figure 38 as the calculations would be the same for the remaining units. With the provided values the amount of cooling could also be calculated by using the energy balance were the sum of the input energy should be equal to the sum of the output energy. This gives a ball park figure as in reality pump work and losses to the surroundings are also a factor, but for simplicity an assumption was made excluding pump work and losses to the surroundings and resistive losses in heat transfer in the heat exchangers. Furthermore, the electrical efficiency was calculated with the stated values were the output (electricity) was divided by the input energy and around 12% was found to be converted to electrical energy. As the units have the same heat demand and electrical output, this gives them the same electrical efficiency ($\eta_{el} = Q_{el}/Q_{heat}$ x 100%) of 11.90%. It is not exactly clear or explained in the presentation or brochure how this can be exactly the same for all four units having different hot side temperatures. However, a way to validate this claim would be, by having study visits to other plants that have already installed such a system. For example, Climeon AB mention on their webpage and video presentation that the steel manufacturer SSAB have also installed an ORC system with the capacity to produce 1300MWh (1.3GWh) of electricity yearly at their plant in Borlänge, Sweden (Climeon AB, n.d.-a). Additionally, if the ORC units can work to lower temperatures such as an exit of the hot side being around 65°C (instead of 70°C) then this would better fit the profile of the plant and especially for the summer periods. Looking at figure 32, during the summer periods, the temperature after VK1 is around 105°C and 65°C before VK1 making this a suitable place to connect the ORC units. To fill in the remaining questions to whether the unit could work and be cooled by the Säveån river and not exceed the environmental rulings this is calculated and presented in figure 39 below.

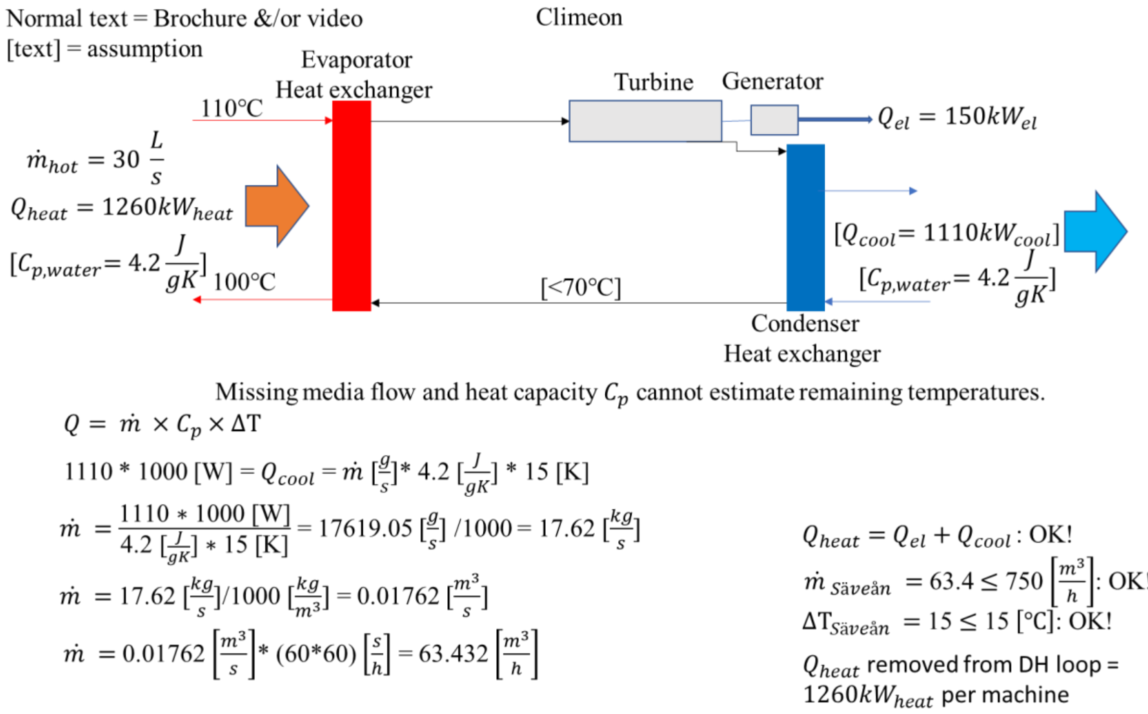


Figure 39: A filled in simple schematic over the ORC unit HP150 with the assumptions mentioned in the previous figure.

With the assumptions made in the earlier figure the amount of water that would be needed form the Säveån river was calculated with the assumption that the temperature difference would be 15°C (which is the maximum allowable temperature difference from the environmental ruling). To find the amount of water needed, the heat energy equation was used and rearranged to calculate the flow ($\dot{m}$) needed. The flow that is needed to cool 1110 kW of heat is around 63.4 m^3/h. This can also be seen in the checklist at the bottom right corner of figure 39, were along with the flow being below the maximum allowable, the energy balance was also checked, along with the allowable temperature difference and how much heat can be expected to be removed from the district heating demand. For the first three machines the same calculations are needed but the exit temperature after the fourth machine is around 70°C, looking at table 15 the minimum temperature before VK1 is 65°C. This was the assumption that was used, to dictate what the temperature should be from the ORC units to the district heating loop. The fourth machine's calculations is shown in figure 40 below.

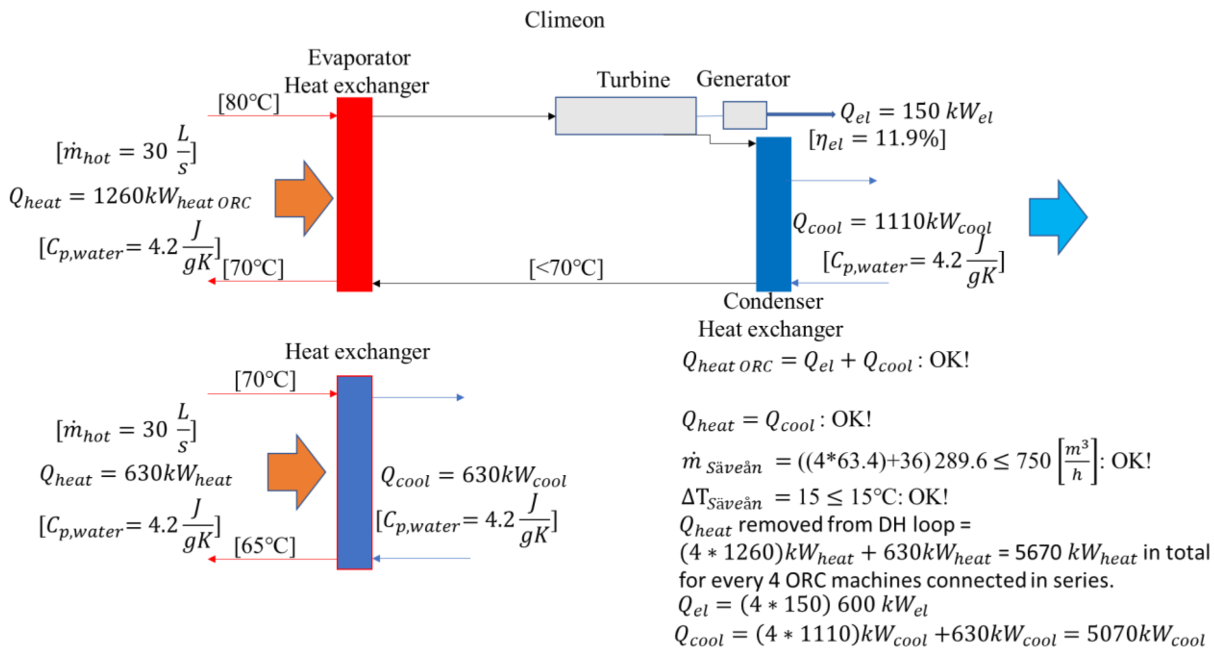


Figure 40: Energy calculations for the fourth ORC unit (HP150) in the series connection along with a short checklist.

The same amount of cooling is expected for the fourth unit but the hot side exit temperature is higher than 65°C which is the assumed temperature that would allow a good connection between the return line from the ORC and the district heating loop. To bring the temperature from 70°C to 65°C a heat exchanger was modelled were it was assumed that there was no pressure drop across the heat exchanger which meant that the pump work could be neglected. Overall the same assumptions were used to calculate the values in figure 40 as the ones in figure 38. A checklist is also provided in figure 40 were it can be seen that with four ORC units connected in series the expected amount of heat that is removed from the district heating loop is around 5670 kW. From four units the expected electrical output can be 600 kW while the cooling demand from the Säveån river would be around 5070 kW. This means that such a configuration would also work when the amount of cooling from the Säveån river was restricted to 5.9 MW (from figure 30 on the 15th of September at 10 in the morning). Additionally, as there is some more room for cooling available from the Säveån river, a configuration where the flow could be doubled, and another four ORC units could be connected in parallel would also work. Keeping all other parameters the same except increasing the hot side flow to 60 L/s would result in a mass flow of the water from the Säveån river being 579.2 m^3/h (which is still within limits), a total heat reduction in the district heating loop of 11340 kW, an electrical output of 1200 kW and a total cooling demand of 10140 kW (which is lower than the 13 MW limit). Figure 41 below illustrates a simple representation of the configuration that can be said with relative confidence that could be applicable for the Sävenäs plant.

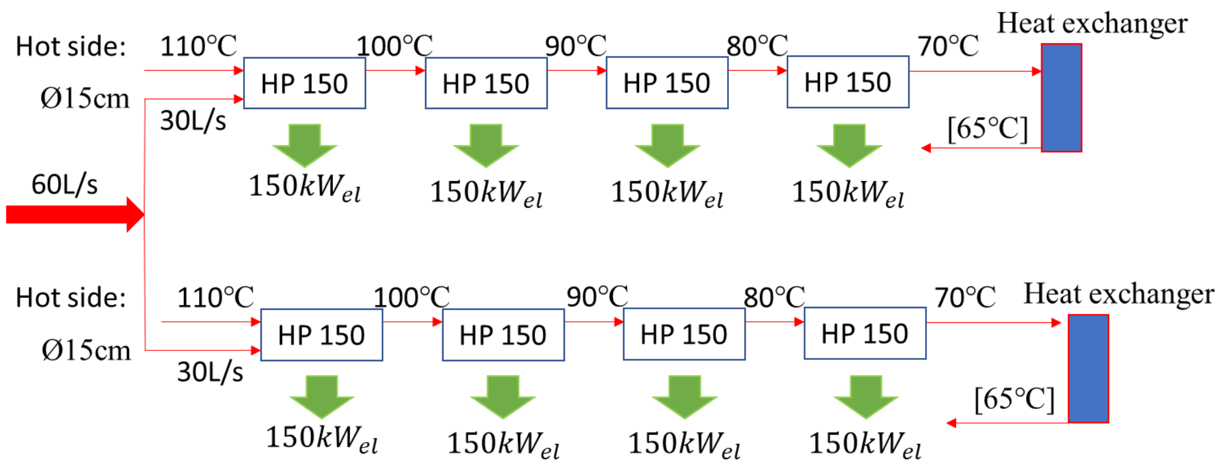


Figure 41: Simple schematic of the ORC units that the Sävenäs plant could use and have enough cooling from the Säveån river.

With the configuration shown in figure 41 and the expected demand and energy reduction from the district heating loop a considerable amount of cooling is expected. Looking at figure 35 the amount of hours that such a configuration could be expected to run is around 90-95% of the time that the cooling towers were run for 2019. This is seen as an extremely good amount of time that the ORC units would be working. Additionally, this can also be seen as increasing the total amount of cooling that the Sävenäs plant can provide to its customer (max 71 MW from cooling towers + 11.3 MW from ORC) to a total of 82.3 MW's of cooling. Furthermore, when it comes to the energy aspect of these units assuming around 2600 running hours for 2019 and allowing all units to be run would result in 29380 MWh (11.3 MW * 2600 hrs) of cooling and 3120 MWh (150 kWel * 8 units * 2600 hrs) of electricity. Assuming conservatively that the only large cost are the units themselves (excluding maintenance costs) over a 10 year lifespan would give an electricity price of 89.74 Euro/MWh ((350000 € * 8 units)/(3120 MWh * 10 yrs.)). This alone would make the project too expensive and not competitive, especially considering that this would be during the summer periods when electricity prices are low to begin with. However, if an agreement could be made were the plant also gets paid for each MWh of energy that is cooled this could help bring the electricity price down. Additionally, this can be seen as being a worst-case scenario when it comes to running the units and the lifespan, increasing both these values also decreases the electricity cost. This can be seen as an extremely rough estimate and such units may be seen as paying themselves off through indirect generation of income. For example, by having study visits from other companies and positive public relations where it is shown that energy utilisation is tested to try and make the world a better place.

For ease of illustration a possible connection of the ORC units is shown in figure 42 below.

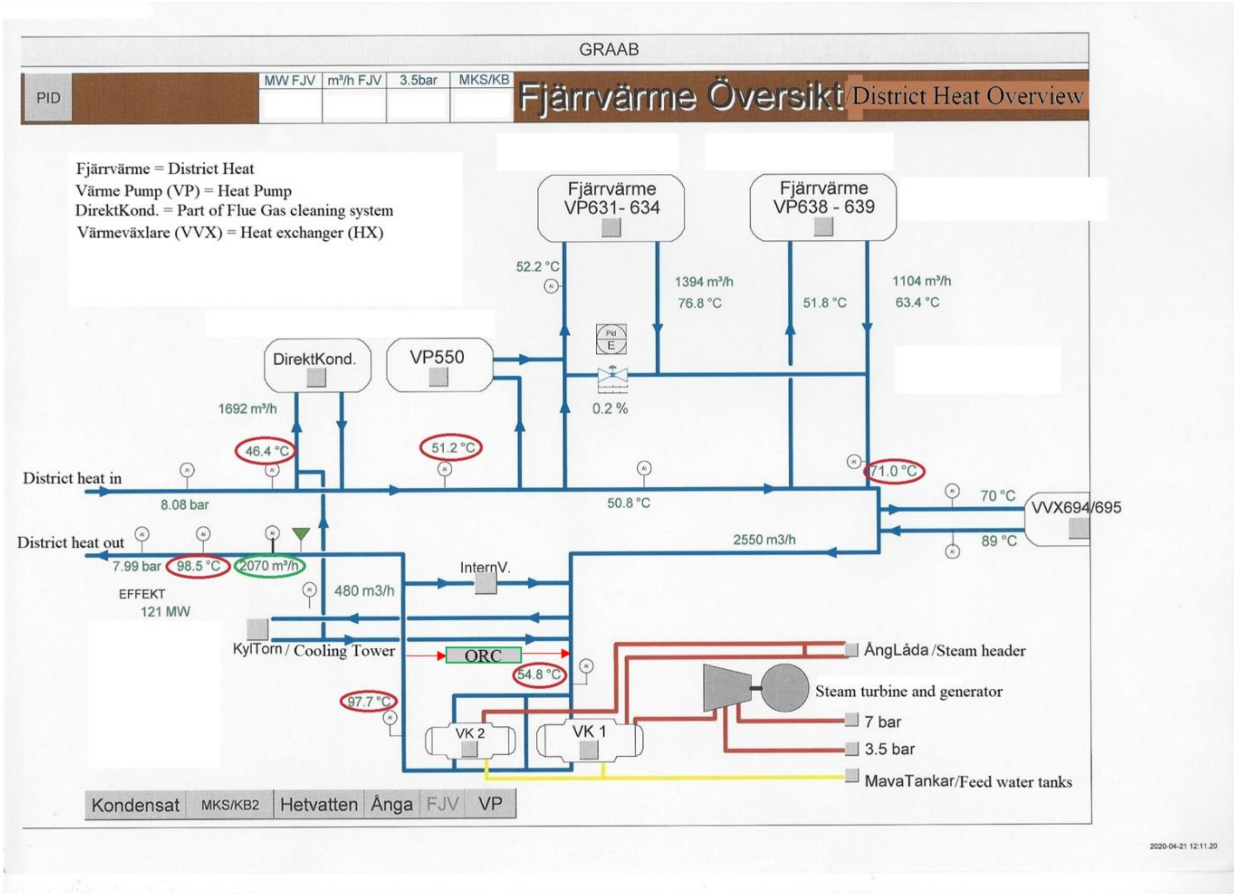


Figure 42: District heating overview across Sävenäs plant on a hot day with the cooling towers just being turned on and a possible connection for the ORC units across VK1 (Copyright given by personal correspondence with Renova).

With the temperatures given in figure 42 it may seem that an ORC unit would not work well, but it should be kept in mind that this print screen was taken during the time the cooling towers were starting to stabilise the temperatures and especially the flow of the district heating loop. Looking back at figure 32 and the temperatures before and after VK1 are around 70-65°C and 110-105°C respectively. For the Climeon AB case the hot side was chosen to be 110°C rather than 105°C as this allowed a best-case scenario for what the temperature could be expected for the ORC units. Additionally, taking 110°C allowed for an even 10°C drop across each of the four machines which if felt as being very close to the example given during the presentation and allowing the assumption of having 10°C across the fourth and final unit and still be at the 70°C boundary of the manufacturer.

In the review from F. Vélez et al. it was seen that from multiple cases the overall efficiency increases using ORC, for example by attaching a bottoming ORC unit to a typical steam driven geothermal plant, the overall efficiency increased by 9% (Vélez et al., 2012). This could also be the case for the Sävenäs plant in allowing the steam turbine to run at maximum by keeping the flow of district heating through the steam condenser (VK1) and varying the district heating delivered to Gothenburg Energi by allowing the ORC to take the fluctuations. This would result in more running hours for the ORC, less drastic fluctuations in district heating flow through the Sävenäs plant and fully maximising the steam turbine. Additionally, this would further help in bringing the cost for produced electricity down.

The second ORC company that was found that could supply ORC units was Againity AB. Through a study visit, webpage and brochure analysis along with email correspondence various information was gathered about their machines. Currently they are building their 19th unit and the largest ORC unit that they have built and delivered was a 0.5 MW_{el}. Additionally, unlike Climeon AB who only sells one type and size unit, Againity AB instead can tailor build an ORC unit based on the customer needs. On their brochure they have sizes ranging from 50 kW_{el} up to 2500 kW_{el} (possible examples of unit sizes) and during the email correspondence an example was given that for a specific customer a 130 kW_{el} unit was delivered, which was not one of the examples in the brochure (Againity AB, n.d.). Furthermore, the working temperature of the ORC unit delivered from Againity AB is different from that of Climeon AB. The boundaries for these temperatures and flows are shown in table 20 below.

Table 20: Againity's AB ORC unit boundaries for temperatures and flows. Source of values: (Againity AB, n.d.) & (E. Ledskog personal communication, April 29, 2020).

	Hot side [°C]	Hot Side Flow rate [L/s]	After condenser [°C]	Cold Side Flow rate [L/s]
Max.	150	-	80	-
Min.	90	-	-	-

The temperature boundaries and flows are 150-90°C for the hot side and regarding the cold side, the only limitation is the maximum temperature after the condenser which is around 80°C (E. Ledskog personal communication, April 24, 2020). The maximum temperature after the condenser is probably the limit for the media to phase shift from gas to liquid. In table 20, the flows for both the hot side and cold side are not specified since it was explained that the larger the flow, the larger the heat exchanger needed, which follows in line with tailor made machines. No other limitations were specified for the ORC unit from Againity AB, the only thing when it came to the flows was that their smallest unit is a 50 kW_{el}, meaning flows lower than that cannot be met by them. Regarding the efficiencies of the units it was stated that the temperatures out from the evaporator and the condenser dictate the unit's efficiency. Ultimately these are the dictating parameters, the higher the temperature out of the evaporator, the more energy that can be transferred to the turbine. The lower the temperature out of the condenser the more energy is available for uptake from the media (more available capacity). After being asked what the efficiency of the machine during normal conditions could be, it was stated that as they work with large variations in flows and temperatures the efficiencies also vary greatly and that's why they don't have any normal conditions. It was mentioned that the maximum possible efficiency, for the larger units (greater than 1 MW_{el}) are expected to be around 15-20% but Againity AB have not built any physical units of this size yet, thus, there are no references to verify expected efficiencies (E. Ledskog personal communication, April 24, 2020). Furthermore, the ORC machines from Againity AB are suggested to be connected in parallel rather than in series unlike Climeon's who can do both. Being connected in parallel means that they divide the flow but keep the same temperatures entering the machines.

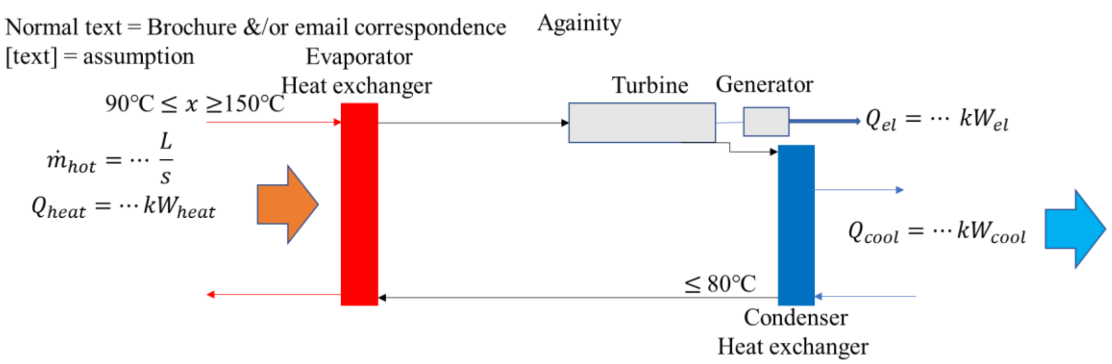
As mentioned earlier a study visit was performed to Alvesta Energi on the 30th of January 2020, were Againity AB had installed their smallest unit of 50 kW_{el}. Figure 43 below, shows the ORC machine at Alvesta Energi.

Figure 43: Smallest ORC unit from Againity AB capable of producing 50 kWel installed at Alvesta Energi (Picture personally taken by author and copyright given by personal correspondence with Againity).

In figure 43, the electrical box (1) with the user interface panel (2), electricity values display (3), an emergency stop button (4), a mains disconnect switch (5), a button and a toggle switch (6) can be seen. Additionally, in figure 43 the silver coloured pipes contain the hot and cold flows going to and from the machine (7) and the frequency-controlled pumps (8). The reasoning behind pointing out these components is to both give some explanation to the reader with what is seen, but also in a way point out how few components that are used. It is obvious that the inner workings are not shown, but from a customer side, not a lot of input or control over the system is needed. Furthermore, the 50 kW_{el} ORC unit is called AT50 on Againity's brochure and the dimensions are, length x width x height of 3.5 x 1.6 x 2.1 metres respectively (Againity AB, n.d.).

Discussing with the Againity team during the study visit an example was given were a biogas boiler which used an ORC system had over 1200 starts. It was explicitly asked how sensitive the machine is to starts and stops and besides the example it was assured that the system can handle many variations without risk of damage to the equipment (such as for steam turbines, standing still for too long can cause the turbine axle to bend). When it comes to overwatch of the unit, it can be continuously monitored electronically but a physical check should be made around once a day. Furthermore, when it comes to servicing the ORC machines, a 12-hour service interval is suggested once a year. When it comes to starting and stopping the ORC machines especially for larger machines it is recommended that you ramp up and down smoothly (ramp down approximately 10-minute intervals/period to be kind to the machines). Also, hitting the emergency button on the panel stops the machine immediately. When it comes to starting the machine, it takes approximately 10-15 minutes. With this said, a possibility could be that if the customer requires quicker cooling of the district heating loop, faster than 10-15 minutes, then the cooling towers could be used first. When the ORC system is up and running the capacity of the cooling towers can be reduced so that the aggregated amount of cooling from both the ORC and cooling towers meets the customer demand.

Combining the information gained from the online research, email correspondence and the study visit, the following section tries to summarise and combine the previous parts to reach a suggestable configuration of an ORC machine from Againity AB. Figure 44 below, tries to give the reader a simple overview of the ORC system and the values provided by Againity AB along with a list of assumptions that are used to fill in the blanks of the model.



[Given max temp. out of condenser 80°C therefore lowest temp. out of evaporator assumed 81°C.]

[Assume no pressure loss across heat exchangers or pump work needed to pump media around (ball-park values).]

[Assume perfect heat transfer between heating and cooling media (no resistive losses). Allows for easier guess of missing temperatures, if needed during calculations.]

[Assume heat capacity C_p of water, $C_{p,water} = 4.2 \frac{J}{gK}$.]

[Assume $\eta_{el} = 10\%$ to be conservative as they claim higher efficiencies for units that are larger and not yet built.]

[Claim larger flow, requires larger heat exchanger. Not sure what a reasonable size can be, therefore, assume same flow as in Climeon example, $\dot{m}_{hot} = 30 \frac{L}{s}$.]

[Renova hot side connections that are analysed are around VK1, temps. After VK1 105°C before 65°C. Assume hot side 105°C-81°C. And remainder needed to be cooled with heat-exchanger from Säveån.]

Figure 44: Simple schematic over the ORC unit and values provided by Againity AB through email correspondence and the assumptions used.

When inserting the values provided via the email correspondence or the brochure it can be seen that quite a few parameters are left unfulfilled. To try and fill in the blanks, multiple assumptions were made, as can be seen in figure 44. The assumptions are made to try and fulfil the heat energy equation and what the Sävenäs plant can deliver and receive in terms of extracted temperatures and returned temperatures along with flows. Additionally, these assumptions are made to give a ballpark figure rather than a detailed, completely accurate and finished analysis. For example, at this stage it is seen as acceptable to omit from taking into consideration the pump work needed or that there is some heat transfer resistance in the heat exchangers. Figure 45 below, combines the assumptions made in figure 44 along with verification calculations for the energy and flow that is needed from the Säveån river.

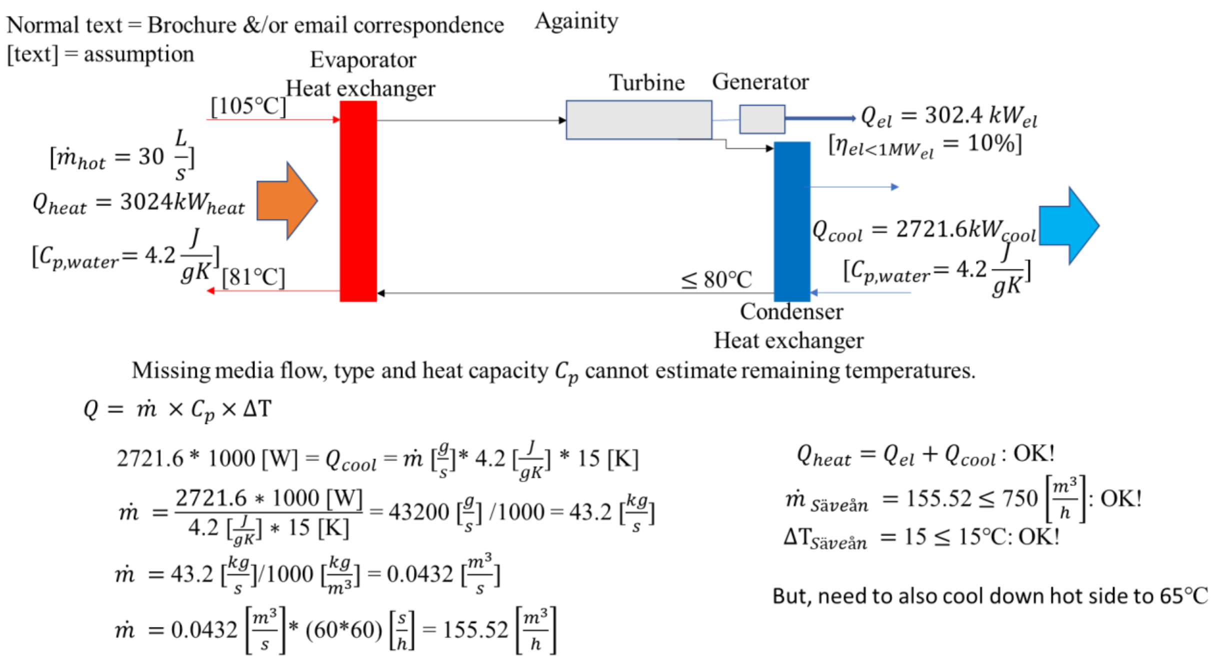
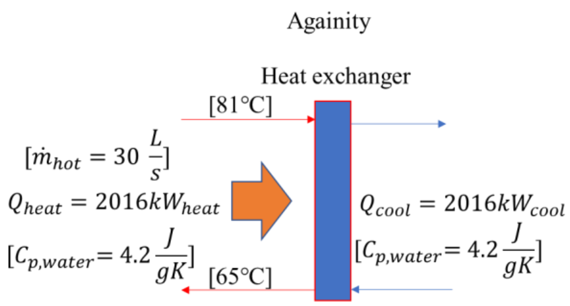


Figure 45: A filled in simple schematic over the ORC unit with the assumptions mentioned in the previous figure.

To begin with, in figure 45 the temperature of the hot-side was maximised for the unit (ΔT = 24°C) , in comparison to Climeon AB were each unit can take up around 10°C. This was primarily done to hopefully allow for a smaller footprint of the unit. The volumes for the example units from the brochure are calculated to be 28.7 m³ and 34.5 m³ for the 200 kW_{el} and 500 kW_{el} units respectively (Againity AB, n.d.). Taking the aggregated values from table 19 for the Climeon AB 150 kW_{el} unit, a volume of 37.25 m³ was calculated. Roughly speaking the tailor-made unit can have a smaller size than a standard size unit made to fit the plants criteria. Furthermore, from the mass flow calculations made in figure 45, it can be seen that there is some margin for expansion when it comes to the environmental ruling boundaries. A small checklist can be seen in the bottom right corner of figure 45, were the energy balance over the unit, flow and temperature difference (ΔT) were fulfilled. Furthermore, as the outlet temperature from the hot side (evaporator heat exchanger) is higher than what the temperature before VK1 (seen in figure 32) is, this has to be cooled further. Figure 46 below, shows a simple schematic of the heat exchanger used to cool down the remainder of the hot side from 81°C to 65°C along with the assumptions made and the mass flow calculations for the river.



[Assume no pressure loss across heat exchangers or pump work needed to pump media around (ball-park values).]
[Assume perfect heat transfer between heating and cooling media (no resistive losses). Allows for easier guess of missing temperatures, if needed during calculations.]

$$Q = \dot{m} \times C_p \times \Delta T$$

$$2016 * 1000\ [W] = Q_{cool} = \dot{m}\ [\tfrac{g}{s}] * 4.2\ [\tfrac{J}{gK}] * 15\ [K]$$

$$\dot{m} = \frac{2016 * 1000\ [W]}{4.2\ [\frac{J}{gK}] * 15\ [K]} = 32000\ [\tfrac{g}{s}]\ /1000 = 32\ [\tfrac{kg}{s}]$$

$$\dot{m} = 32\ [\tfrac{kg}{s}]/1000\ [\tfrac{kg}{m^3}] = 0.032\ [\tfrac{m^3}{s}]$$

$$\dot{m} = 0.032 \left[\frac{m^3}{s}\right] * (60*60) \left[\frac{s}{h}\right] = 115.2 \left[\frac{m^3}{h}\right]$$

$$\dot{m}_{sum} = 155.52 + 115.2 = 270.72 \left[\frac{m^3}{h}\right]$$

$Q_{heat} = Q_{cool}$: OK!

$\dot{m}_{Säveån} = 270.72 \leq 750 \left[\frac{m^3}{h}\right]$: OK!

$\Delta T_{Säveån} = 15 \leq 15$°C: OK!

Q_{heat} removed from DH loop =
$3024kW_{heat} + 2016kW_{heat}$ = 5040 kW_{heat} in total

Figure 46: Simple illustration, including assumptions for remainder of energy that needs to be cooled before being sent back to district heating loop in Sävenäs plant.

In figure 46 a simple illustration of a heat exchanger is shown to give the reader a visual representation of how the hot side fluid can be cooled with the Säveån river. The assumptions made were that there is no pressure drop or resistive losses across the heat exchanger simplifying the need to take pump work into account. Furthermore, a calculation was made to calculate what the flow from the Säveån river would be to cool the desired amount. Additionally, a check list was made were the energy balance and the environmental rulings were met. In short, removing 5040 kW_{heat} from the district loop (cooled) can result in 302.4 kW_{el} of electricity being produced. If the idea is to maximise the available and allowable cooling from the Säveån river then the flow of hot water could be increased or working from the available cooling backwards to the heat demand needed. Figure 47 below, shows the maximum size that the ORC unit could be based on the allowable cooling available from the Säveån river.

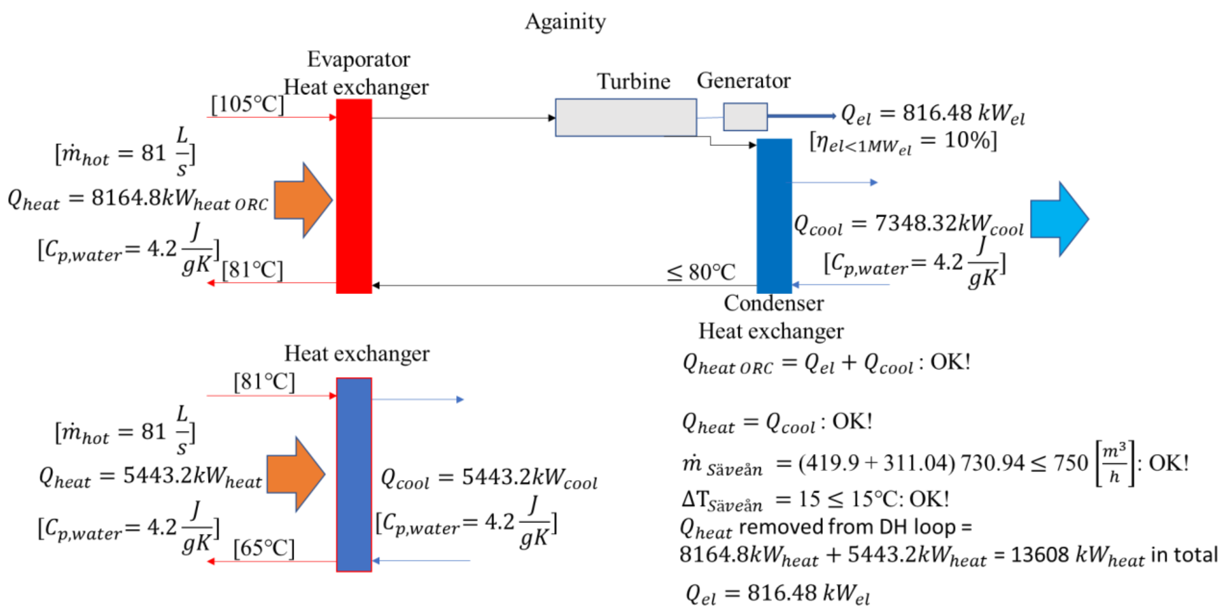


Figure 47: Maximum size of ORC unit based on the available cooling from the Säveån river.

From figure 47 it can be seen that a flow of 81 litres per second at the temperatures of 105-81℃ and 81-65℃ would yield an ORC unit with an electrical output of 816.48 kW_{el} and a district heat loop energy reduction of 13608 kW_{heat}. With this said, having a unit of this size would probably be more space efficient but the number of hours that it could possibly run would be reduced. Looking at figure 35 an approximate demand for approximately 13 MW_{heat} from the customer would have the unit run for 2500 hours instead of 2716 hours were demand was below 10 MW_{heat}. In a way, this size ORC unit would still be run for more than 85-90% of the total running hours that the cooling towers were run for 2019 which is still a very good amount of running time in comparison to the total amount that the towers were run. Additionally, this would increase the total amount of cooling that the Sävenäs plant can provide to its customer (max 71 MW from cooling towers + 13.6 MW from ORC) to a total of 84.6 MW of cooling.

Comparing the two configurations from the companies it can be said that the one from Climeon AB might take up some more space as each unit is a fixed size whilst Againity AB might be smaller due to it being tailor made (units with same hot side flow of 30L/s). What still remains to be answered for both machines is what their minimal flows to the units could be (i.e what is the working range of the machine). The ORC unit that is configured in figure 47 might not work with a reduced flow to the extent that was seen on the 15th of September, were the available cooling from the Säveån river was around 5.9 MW (instead of max 13MW). Rounding off from these calculations it is felt that there is some room for such a system to be installed at the Sävenäs plant, the actual size would have to be verified based on more parameters (for example space, more details for the economic calculations etc.)

A case could also be made if more actors (not just within the Sävenäs plant) were involved such as Gothenburg Energi. An ORC unit could be placed at Holmen helping to run the electrolyser for the hydrogen station and the cold side could be fed from the Göta river (Göta Älv). In doing so, there would be more cooling available (as Göta river is larger than Säveån river) allowing the unit to be larger, helping take advantage of the excess heat in the summer and generate more electricity.

When it comes to the electrical generation the Climeon AB setup could potentially produce 3120 MWh (8 units x 150 kW_{el}/unit x 2600 hr/yr. = 3120 MWh_{el}/yr.) of electricity or 3.12 GWh of electrical power per year. While the Againity AB setup could potentially produce 756 MWh of electricity (1-unit x 302.4 kW_{el}/unit x 2500 hr/yr. = 756 MWh_{el}/yr.) or 0.76 GWh of electrical power per year. Againity's setup provides more cooling but less electrical generation in comparison to the Climeon setup that provides more electrical generation than cooling. With this said both setups would provide enough electrical energy to cover the theoretical yearly demand for the hydrogen truck (0.6 GWh of electricity). This comparison was done assuming the same hot side flows. In the case of Againity if a single unit designed based on the maximum available cooling was instead used the expected electrical supply would be around 2 GWh of electricity (1-unit x 816.48 kW_{el}/unit x 2500 hr/yr. = 2041.2 MWh_{el}/yr.) which would still be more than enough electrical supply for the HRS station.

4.2 Turn-key hydrogen refuelling station companies

In the following section some companies that were identified to offer turn-key hydrogen refuelling stations (HRS) options are analysed. It should also be noted that four out of the five companies analysed below do offer a turn-key solution while the fifth company that was contacted only focuses on the electrolyser side. In the technical section of the report it was mentioned that the assumed energy demand for the hydrogen refuelling station would be around 57.9 kWh of electrical energy. The energy allocation was 47 kWh/kg for the electrolyser/electrolysis, 5.6 kWh/kg for the compressor and 5.3 kWh/kg for the ancillary equipment, also called Balance of Plant (BOP). Furthermore, the demand of 28kg/day of hydrogen equally divided in 24 hours results in an hourly demand/production need of 1.17 kg/h (28 kg/day ÷ 24 h/day = 1.167 kg/h). This can also be converted to Nm^3/h, for 1.17 kg/h demand conversion is equivalent to 12.99 ≅ 13 Nm^3/h (assuming a pressure of 1 atmosphere and 0°C) (Universal Industrial Gases, 2017).

4.2.1.1 Nel ASA

Nel ASA (can also be referred as Nel) is a company in Norway that focuses on renewable hydrogen production through electrolysers but also offers the fuelling aspects to customers. In short, they offer complete turn-key solutions. Something interesting about the company is that its timeline starts from 1927 were testing was done with electrolysers to try and provide pure hydrogen for fertilizer production. This is stated to further reinforce how well known and used this type of technology has been in industry. In a way what is happening now is more of a transition to commercial public use (as before it was primarily used only within industry) (Nel ASA, n.d.-a).

As multiple companies who offer turn-key HRS were planned to be contacted the questionnaire found in appendix B was created to try and create an even playing field that would allow the best possible comparison between them. Unfortunately, even with the best intentions this was not realised. Moving along, it needs to be stated that among the companies that were contacted Nel was one of the few companies that answered most questions on the questionnaire and responded within the same day. This in a way shows that they at least have the capacity to take the time and review inquiries.

What can be extracted from the answers from the questionnaire is that Nel does offer a complete turn-key HRS that can meet a daily demand of 28 kg/day. Additionally, for a HRS with a supply of 28 kg/day, Nel would require from the customer an electrical supply of 3 x 400 volts and demineralised water. The type of electrolyser that is recommended to meet Renova's need would best be met by a PEM electrolyser. As Nel provides both PEM and alkaline electrolysers it was mentioned that the alkaline electrolyser uses an electrolyte consisting of potassium hydroxide (KOH) in a 25% mixture in water. The expected electrical energy demand allocation for such a HRS would 50 kWh/kg for the electrolyser, about 5 kWh/kg for the compressor and 5 kWh/kg for the remainder parts (BOP). The sum of electrical energy required by the HRS is around 60 kWh/kg which is very close to the theoretical calculation used in the report (57.9 kWh/kg). This is very good as it allows for comparative results and conclusions reached throughout the report to be closely relatable to the Nel HRS case (i.e. if a result or conclusion is reached for 57.9 kWh/kg it can be seen as being representative of an actual HRS case from a company). The most common way of storing the produced hydrogen on site is via pressure vessels (compressed gas canisters/tanks). Furthermore, Nel does offer a HRS that can produce/work with a varied supply of electrical energy (i.e. production can vary according to electrical supply from the solar cells). The expected delivery time for such a project is estimated to be around 8-10 months where the time for installation, commissioning and start up takes about 2-4 weeks. Nel can help the customer meet their needs, for example, by providing on-site support, training etcetera. Finally, if a 350 bar HRS is initially commissioned no major changes would be needed to said station later on if Renova wished to allow for 700 bar refuelling capabilities as well (B. G. Halvorsen, personal communication, March 24, 2020).

Browsing the webpage of Nel some potential products that were viewed seem to be very similar to some information given from the questionnaire. For example they offer a hydrogen station called H2Station™ (SM) that has the capability of 350 bar (at 120 kg/h refuelling capacity) and 700 bar (65kg/h refuelling capacity) pressures and requires around the same electrical supply (200A 3x400V) as mentioned in the questionnaire. Additionally, it has a dispenser option of 35 MPa (or 350 bar) pressure suited for heavy duty vehicles with a capacity of 10-50kg (called DI002). The dimensions of the H2Station™ is 3.3m long, 2.2m wide and 3.6m high giving it a footprint and volume of 7.26 m^2 and 26.14 m^3 respectively. From the author's understanding this unit comprises only of the compressor which can be used for both storing the hydrogen on site and in the vehicles during refuelling. Additionally, it is advertised as the world's most compact hydrogen station (footprint wise) (Nel ASA, n.d.-b). Furthermore, Nel offer a hydrogen supply storage (called (SS001) which uses type I canisters to store hydrogen gas at 200 bar (nominal) pressures. The maximum storage capacity of each storage rack is 500 kg of hydrogen, were if needed more racks can be added to increase capacity. Two types of dimensions are given and as no clear distinction is made (other than short or long) the largest of two will be mentioned (mention biggest footprint as being able to accommodate the largest will automatically mean the smallest can also be accommodated). The footprint and volume of the hydrogen supply storage is 29.52m^2 and 88.56m^3 respectively (Length: 12.3m, Width: 2.4m, Height per layer (max. 5 layers): 0.6m x 5 = 3m) (Nel ASA, n.d.-c). Combining the footprints of the station and storage results in a required area of 36.78 m^2 (7.26m^2 + 29.52m^2) with a storage capacity of 500 kg of hydrogen. From the author's understanding if a fast refuelling is desired for the turn-key HRS an intermediate storage device is needed, between the compressor and tank on-board the vehicle. However, this is only needed/available for the 700 bar option and will not be considered further in the report. Furthermore, as no electrolyser is mentioned in either units (both from personal correspondence and webpage), it will be assumed that more area would be needed if an electrolyser was included. With around 500 kg hydrogen storage this would be enough to refuel the truck for 17 days (500/28 = 17.85 days) without needing to produce any hydrogen. This could be an option if the solar cells are desired to be utilised more than just producing enough hydrogen for one day only. The limiting factors would be the space needed to accommodate the station, the storage and the added cost of having to store that much hydrogen (instead of only having enough storage to meet daily demand (being the minimum cost)).

On Nel's webpage they also have multiple categories of electrolysers (according to production size) which use PEM or alkaline electrolyser technologies. The alkaline electrolysers (called A series and A series containerized) are more suited for larger more stable production, for example the A series have a capacity of 3 880 Nm^3/h or around 8 ton of hydrogen per day. The PEM electrolysers have a wider working production span from the S series (most suited for laboratories) that have a capacity of 1.05 Nm^3/h to the M series (which also come in containerised units to save space) with a capacity of 4 000 Nm^3/h. All PEM electrolysers provide a gas quality of 99.9998% (or 5.8) and the larger PEM units are very well suited for renewable energy applications. Both alkaline and PEM electrolysers can be made to work as turn-key solutions (Nel ASA, n.d.-d).

The fact that Nel has such a large variety of green hydrogen production equipment/series, the ability to provide complete turn-key hydrogen refuelling stations and help the customer run the station indicates that they could be a possible candidate for helping Renova meet their needs either now or in the future (1 hydrogen truck per day or for around 30 by 2030). Also, as it was not specified how large the footprint would be of such a station, assuming that the containerised electrolysers (assumed single 40ft container, around 29.74 m^2) along with the station (HS) and storage (SS001) would be sufficient to meet Renova's demand an expected footprint of 67m^2 (29.74m^2 + 36.78m^2 =66.52m^2). Even with an addition of the container for the electrolyser the overall size of the HRS is small.

4.2.1.2 Fronius

Fronius is a company that is headquartered in Austria and its main areas of operation range from welding technologies to battery charging and photovoltaic systems (in a way the common denominator between these technologies are the inverters which Fronius makes). Within the photovoltaic systems the hydrogen aspect is also found were since 2002 they have been researching and developing hydrogen and fuel cells. Looking through the Fronius website some information could be gathered regarding the hydrogen station. It was felt that if Fronius could also answer the questions found in appendix C of this report it would help give an indication how well it would meet Renova's needs. Unfortunately, it was quite difficult to get a response to the questions but by directly contacting the technical sales manager Mr. Mittermaier some of the questions were answered through the phone and a webinar link was sent to hopefully help answer some of the asked questions (D. Mittermaier personal communication, May 18, 2020). Mr. Mittermaier did verify that Fronius does offer a turn-key hydrogen refuelling station and a station with a capacity of 26 kg/day at 350 bar was possible (probably being the closest to one of Fronius station designs) (D. Mittermaier personal communication, May 18, 2020).

In the webinar and homepage of Fronius many interesting things are mentioned regarding the hydrogen station (Fronius calls their station SOLH_2UB, pronounced SOLHUB). In short, the company only focusses on green hydrogen, primarily through photovoltaics as the company offers such solutions, the electrolyser is of the PEM type, the type of storage containers used for the produced hydrogen are of the compressed gas type (rather than liquified hydrogen), a dispenser (350 and or 700 bar) and finally the SOLHUB can also have a fuel cell that can be used to produce electricity. The expected applications of the SOLHUB are within the transport sector, re-electrification via a fuel cell where hydrogen is produced during excess electricity for example during the summer period when demand is low but PV's produce the most electricity, this can be converted to hydrogen, stored seasonally and supplied back to the grid when demand is higher (e.g. during the winter periods). Additionally, running the SOLHUB produces heat and by utilising the excess heat for example by heating nearby buildings the system efficiency increases. A combination of using the excess heat to heat buildings and transport could be of use for Renova to begin with. The maximum hydrogen production capacity of a single PEM electrolyser is 52 kg/day, but it can be both scaled up (by having multiple units) or scaled down (use fewer components). It was mentioned that the reasons why Fronius uses PEM electrolysers over alkaline or solid oxide electrolysers are they have small production capacities, high operating pressures, easily scaled up or down and can be perfectly linked with renewables such as PV's. The alkaline electrolyser uses for example 40% KOH solution which puts high strain on materials and is not an optimum solution for Fronius. The solid oxide high temperature electrolyser is seen as in general still being in the development stages and thus not used. The SOLHUB station can provide hydrogen gas with a purity of 5.0 (99.999%) and output pressures of 350 and or 700 bar (following the international industry standard). The requirements from the customer (location of the station) is that the water supplied to the electrolyser is demineralised and a mains connection to allow for peak electrical loads from the grid during summer seasons (e.g. via solar PVs) and stored in the form of hydrogen for later to be converted back to electricity by using the fuel cell. Additionally, some of the medium-term plans for Fronius is to get the cost of green hydrogen to around 10-12€/kg. This cost might be greater than the calculated cost earlier, but it should be noted that it was only considering the cost of electricity and no maintenance or investment costs. This shows how high the prices can be for decentralised small production scale units. Furthermore, due to the modularity and design of the station it can be upgraded to more efficient components later on and also increase capacity with the same station. It was stated that the SOLHUB needs 50 kWh of electrical energy to produce 1 kg of hydrogen (Fronius, n.d.; YouTube, 2019b).

It was not clarified what was included in the electrical energy demand of 50 kWh to produce 1 kg of hydrogen, but it is within the same ballpark as the derived value of 57.9 kWh/kg from the report. The most interesting aspect of the SOLHUB station from Fronius besides being a complete turnkey solution is that the company also offers the solar cell aspect. If Renova were to try and implement a green hydrogen production and refuelling station Fronius's solution seems to be a one stop shop helping simplify a lot of the integration between the two aspects of the project.

4.2.1.3 Hydrogenics

Hydrogenics is a company headquartered in Canada that works on developing and supplying fuel cell and hydrogen generation products and has been active in the field for over 60 years. The parent company who owns Hydrogenics is the diesel engine manufacturer Cummins Inc. (Hydrogenics, n.d.).

Hydrogenics seem to have standardized modules for hydrogen production to try and keep prices down. The standardised sizes that they have are 22, 32, 65, 130 kg/day and even larger hydrogen production units. Furthermore, it is mentioned that the units can have a wide range of operation from 10-100% of the capacity. Additionally, the units are modular and extendable in their capacities. Also, Hydrogenics offer a "one control system" over the entire HRS allowing for remote monitoring and simplistic use. The fuel grade of the hydrogen from Hydrogenics is stated to be around 99.999% (or 5.0) making it a perfect candidate for use in PEM fuel cells. The expected electrical demand for the whole HRS would be around 65 kWh/kg for 350 bar system and 68 kWh/kg for the 700 bar. Assuming the increase of 3 kWh/kg from 350 to 700 bar is only due to the extra compressor work, this follows the theory well where doubling in pressure does not automatically mean a doubling in energy consumption. Hydrogenics have partaken in building more than 40 HRS across the world with examples in Belgium, Germany, Norway, Los Angeles USA, Switzerland etcetera. The station in Germany is stated to be the largest in the world with a capacity of 780 kg/day for both 350 and 700 bar refuelling capabilities (probably the largest for onsite production HRS) (Hydrogenics, 2013).

Besides the information mentioned above, the questionnaire found in appendix B was also sent to Hydrogenics. Interesting pdfs were sent in the response but unfortunately it was also stated that for the business year Hydrogenics does not promote hydrogen refuelling stations as a turn-key solution. It was also stated that they have increased the number of HRS that they have participated in to around 50. Instead of providing complete turn-key HRS Hydrogenics will focus more on the electrolyser parts of a production regardless of the electrical energy supplied (either grid or renewables). In one of the pdfs a HRS that uses a PEM electrolyser and is one of the standard units (called HyLYZER-200-10), can produce 200 kg/day of hydrogen at pressures of 350 and/or 700 bar pressures with a footprint of 3-4 40 foot containers (4x29.74 = 118.96 m^2) (M. Melcher, personal communication, March 27, 2020).

Initially the solutions and services from Hydrogenics looked like a good alternative for Renova, for example, by acquiring a 32 kg/day unit could have allowed running it on partial load to meet initial demand and have some buffer if solar cells were used. At the same time Renova would not get locked in with one size unit which cannot be upgraded in the future. Furthermore, the simplicity of being able to have an overview with one system would allow for easier training of personnel and problem solving. Unfortunately, as the company itself does not provide turn-key solutions it would at least make it difficult for Renova to realise the project.

4.2.1.4 Green Hydrogen Systems (GHS)

Green Hydrogen Systems (GHS) is a company that is headquartered in Denmark. They were founded in 2007 and their core goal is to provide green hydrogen systems (from renewable sources) at a cost that would be competitive to grey and blue hydrogen. It is stated that there are multiple GHS installations in Northern Europe and the company is trying to expand. It is mentioned that they offer modular and standardised electrolysis technologies with on-site production approach (allowing for greater/more energy independence) that would bring affordable/cost-competitive green hydrogen to among others, producers of hydrogen refuelling stations (Green Hydrogen Systems, n.d.-b). An example of a hydrogen refuelling station that GHS was in charge of the project, Engineering, Procurement and Construction (EPC) was in Aalborg Denmark. The company mentions that they typically only serve as an Original Equipment Manufacturer (OEM) for electrolysers but in this case, they were in charge of the entire project. In short, the project was about a refuelling station being powered by renewables that produced hydrogen to refuel buses (Green Hydrogen Systems, n.d.-a).

After multiple attempts both via email and telephone some answers were obtained regarding the company Green Hydrogen Systems in Denmark. In short, they have been extremely busy with expanding their company, trying to move to new larger premises, securing investors and funding which meant that the possibility of answering questions for a thesis report was moved to the very bottom of the priority list. Speaking via the phone it was pointed out that the company now primarily focuses on developing only the electrolyser side of hydrogen production, meaning that they do not offer any turnkey solutions. When asked if they offer any electrolyser units that could supply 28 kg of hydrogen per day, the answer was yes, but it would be on the lower scale of the alkaline electrolysers that they have (A30). A tip was that the unit A30 is a smaller unit of the A60 electrolyser which is slightly altered (remove some components to downscale production) resulting in a slightly lower unit cost (CAPEX) for around half as much of the hydrogen being produced. The larger units A60 and A90 have been compared to other electrolysers in the industry by an external tier 1 global consulting agency which resulted in the units offering the lowest levelized cost for producing hydrogen in the world. Besides the costs of the units, the difference between them is that the A60 produces hydrogen at a maximum rate of 5.4 kg/h while the A30 produces 50% less (2.7 kg/h) and the A90 produces 50% more than the A60 (8.1 kg/h). The biggest difference that was mentioned between the A60 and A90 is that the A90 requires an extra power supply. Furthermore, when it comes to the price of the units no actual price was given but it was stated that the prices are dropping with each year. For example, from 2018 to 2019 the prices dropped by around 10% (N. Baden personal communication, May 13, 2020). This is an indication that the industry is now starting to ramp up production and the full benefit of economies of scale have not been reached yet, and that demand and inquiries are larger than the companies in the industry can handle at the moment.

As the company does not offer any complete turnkey solutions makes it difficult to suggest a solution from them to Renova. If a suggestion was going to be made regarding just buying an electrolyser, then assuming that the prices are similar for A30 and A60 and having a larger unit would allow more trucks to be refuelled (as Renova would like to increase the share of hydrogen driven trucks) then the A60 would make sense. Looking at the brochure that Green Hydrogen Systems has for the A series electrolysers a configuration of A60 at 25% load is shown, which would result in the lowest power consumption (3.77 kW/Nm^3) and highest efficiency (94% Higher heating value (HHV) for just the stack) out of all 3 options and configurations (A30,A60,A90) while delivering around 32 kg of hydrogen per day (Green Hydrogen Systems, n.d.-c). The A60 at maximum stack load would produce 129.6 kg of hydrogen per day (Green Hydrogen Systems, n.d.-c). If each truck requires 28 kg per day, then around 4 trucks could be refuelled fully, and another truck refuelled approximately halfway (i.e. A60 at full load can serve 4.6 trucks).

Green hydrogen offers also a PEM electrolyser, but it only works for much smaller applications. The HyProvide P1 unit can produce hydrogen at a rate of 1 Nm3/h (approximately 0.09 kg/h) (Green Hydrogen Systems, n.d.-d). It is mentioned that the units can be connected in parallel, where an example was given in the brochure that "any number of units can be connected in parallel to supply up to 5 Nm^3/hour of capacity for redundant systems"(Green Hydrogen Systems, n.d.-d). Even with this configuration the expected supply of hydrogen per day would be around 10.8 kg, which is too small even for the initial demand of 14 kg of hydrogen per day, let alone 28 kg/day. The possibility exists for being able to theoretically connect many units in parallel, but it would probably be too complicated and expensive compared to the alkaline electrolysers.

4.2.1.5 The Linde Group

The Linde group has been mentioned in a previous section of the report, to be specific chapter 3.2 which discussed about buying the hydrogen gas and using a compressor on site to refuel the vehicle. In the same brochure that mentioned about the type and footprint of the compressor from The Linde Group it was also mentioned that they provide HRS.

An email was sent to The Linde Group where the questions found in appendix B of the report were attached to the email. A response was received were some of the questions were answered. To begin with it was clearly stated that the company primarily focusses on supplying the hydrogen refuelling station and not the electrolyser. The demand from Renova of 28 kg/day was seen as being too small and the smallest unit from The Linde Group is 28 kg/hour. With this said this type of station could in theory supply enough hydrogen per day to refuel 24 hydrogen powered trucks of the same kind as the one currently owned (28 kg/h x 24 h/day = 450 kg/day). This type of station would be in the middle regarding how well it would help solve the company's issue, for today it's too large and for 2030 when 30 trucks are planned it would be too small. As the questions asked in the questionnaire were questions which required answering (rather than just yes or no questions) this meant that they were left up to the interpretation of the reader (and this goes both ways). This is mentioned as two of the answers were interpreted as contradicting themselves, to try and interpret the answers as accurately as possible the more detailed answer is stated (the question with a better more detailed answer from the responder is used, reducing the need of interpretation). The electrical energy demand for the HRS excluding the electrolyser is around 1-3.3 kWh/kg of hydrogen. Most probably the electrical energy demand of 1-3.3 kWh/kg of hydrogen is for the ancillary equipment (BOP) and excludes the compressor work. This is assumed due to the fact that in the brochure multiple types of compressors (sizes and types (ionic or cryogenic) are mentioned and the value itself is closer to the theoretical BOP calculated in the report (5.3 kWh/kg) rather than combining BOP and compressor work (5.3 + 5.6 kWh/kg). The footprint from the smallest HRS from The Linde Group (450 kg/day) is around 10 metres by 12.2 metres, with an area of 122 m^2. Combining the data from the brochure of the company regarding the area needed by the compressor which was stated in chapter 3.2 (29.74 m^2) and the 122 m^2 needed for the whole HRS, it can be assumed that around 25% of the footprint of the station is taken up by the compressor. Even though The Linde Group does not provide the electrolyser they can integrate the electrolysis system in their design. The suggested type of electrolyser from The Linde Group is of the PEM type (T. K. Schaefer personal communication, May 29, 2020; The Linde group, n.d.).

As The Linde Group primarily offers the hydrogen refuelling stations excluding the electrolyser but, can implement it within their project if an electrolyser is bought from somewhere else this is in a better direction in making their business model suitable for Renova. This is said as there exist many more companies that offer only the electrolysers and fuel cells rather than complete turn-key HRS. This is one of the reasons why only five companies were initially thought of providing such a solution. One did it before but now only focuses on the electrolysers and another provided their services to help build an HRS (more of a one-off build). Also, due to the size of the smallest unit being too large (450kg/day) for the initial demand (28 kg/day) The Linde Group is not the best candidate for now (does not offer a complete turn-key solution).

4.3 Case "Renova"

In this section a possible suggestion is presented of what a hydrogen refuelling station would look like at Renova. As most of the vehicles are found today at the headquarters of Renova (Holmen) this would probably be the most convenient place to have the HRS to refuel the hydrogen truck. The expected lifetime of the HRS was never really discussed or clarified but from the discussion with Magnus Lundström it can be said that it could be from 14 to 29 years (until 20350 or 2050). The delivery time of the HRS would probably be around 10-12 months, and this is based on the answer from Nel but this could also be expected if the effect of the COVID-19 pandemic's effect on the global economy and industries is also taken into consideration. The expected area for the HRS could be as little as 67-119 m^2, were the smaller footprint is from Nel's HRS and 119 m^2 is from Hydrogenics with an example station with 200 kg/day production capacity. It cannot be further developed as to whether this footprint would be too large to fit at Holmen. This is said as the author does not have a good enough knowledge of the Holmen location and the Google Maps image cannot be completely trusted to show an available area of such a size, as was seen during the study visit to the Tagene landfill and the flaring station.

It was seen that enough electrical energy could theoretically be supplied by only installing solar cells at the locations visited or even just at Holmen. If the entire estimated yearly demand of 10220 kg of hydrogen (28 kg/day x 365 day/year = 10220 kg/year) is planned to be stored on site in type I canister bundles, it would require an area of at least 897 m^2 ((10220 kg/year x 9.8 m^2/bundle) ÷ 111.7 kg/bundle = 896.65 m^2/year). As Gothenburg and Sweden in general have an uneven distribution of sunlight throughout the year it would not be advisable to try and produce and store the hydrogen on site (both FLH's of HRS and storage area needed) only based on electricity from the solar cells. This would mean very few running hours for the electrolyser (SMHI expects 2700 hours of sun which would also be the amount of hours for the electrolyser) which would make it more difficult to justify the investment (return on investment would probably be too low). With this said, none of the cases mentioned in figure 7 is suitable to meet the aspects mentioned throughout the report. A "hybrid" version of the three cases would be best suited, this is shown in figure 48 below.

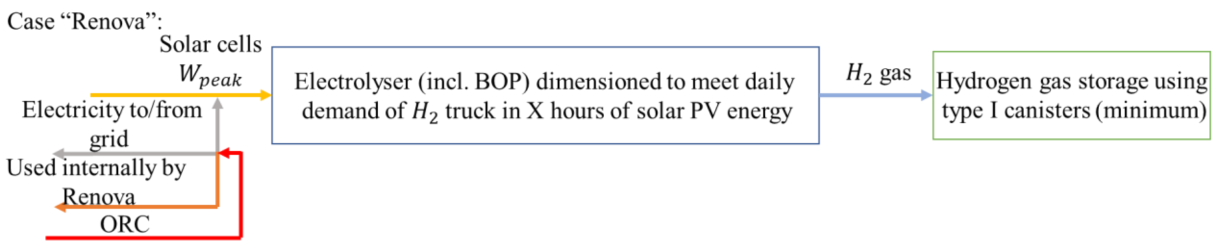


Figure 48: The proposed HRS design for Renova.

From figure 48 it can be seen that for the electrical supply both solar cells and the grid is used. The electrolyser would be dimensioned based on which unit size the chosen company can supply and also how long the solar cells would be expected to supply the energy. For example, assuming that for some days during a year the sun would shine for at least eight hours a day and with those eight hours 28 kg would be produced the electrolyser size would be 3.5 kg/h (28/8 = 3.5 kg/h). The remainder of the year when the sun is not shinning for eight hours the electricity grid would be used to supply the energy to the HRS. With this configuration the electrolyser would be running at a 25% of its total capacity and leave some room for expanding the hydrogen vehicle fleet. The storage of the HRS station would initially be for the single truck as the delivery time on extra canisters is seen as being negligible compared to the remainder of the station and if more storage is needed (permitted that there is more space) it could be achieved in a short amount of time. If all the solar cells or ORC units are installed, then the extra electricity that would be produced could either be used internally by Renova or sold to the grid and also as it is green electricity (100% PV's and 60% ORC) with green certificates that could be sold generating an extra income for Renova.

4.4 Emissions

In the following section some discussion and reasoning will be given regarding the emissions that could be expected from going from diesel and HVO towards electrification. As this is not the core of the report rather than going into specific details a more systematic/overview will be presented.

A telephone meeting was held with Maria Grahn were the basis of the meeting was about various fuels and their environmental impact. Maria Grahn is a Senior researcher at Chalmers University of Technology, at the department of Mechanics and Maritime Science, Maritime Environmental Science. Additionally, Maria is also the Director of Energy Area of Advance for Chalmers University of Technology. Maria provided with helpful insights and material regarding the issues and drawbacks when it comes to accounting emissions. For example, during the phone call Maria mentioned that in the results of some papers they come to conclusions were one alternative is greener than the others (e.g. Expected emission reductions from pine oil HVO to be around 80-90% compared to conventional fossil diesel). This might be the case but one key point that is not taken up by these papers is that the alternative solutions most probably may not be enough to substitute all the current consumption from fossil diesel to one type of HVO oil. In short, it is very good in helping reduce fossil emissions but they're not enough to go around for everyone. This is a point worth noting for decision makers, that in theory the results are good but in reality, there are other issues/bottlenecks that also need to be solved before such a solution is viable (M. Grahn, personal communication, March 18, 2020).

There are three main divisions that can be made regarding transportation. The three divisions are, liquid fuels, electrification through batteries and electrification or direct injection to combustion engines through hydrogen. Liquid fuels are seen as a good alternative as there is already an infrastructure in place but also people have adapted and have gotten accustomed to it. This is one of the main reasons why HVO and other blends of biofuels have been so easily and quickly implemented into the normal lifestyle/use of heavy vehicles using diesel engines (with maybe some modifications needed to the pump and injection system). To a large degree the same trucks and engines can be used to do the job but at the same time being able to choose an alternative fuel that has lowered emissions and impact on the environment. From the discussion it was mentioned that things move a lot faster when people need to make as small to no changes as possible (to their habits) compared to having to get accustomed to a new technology. Some diesel like fuels are, HVO, RME and DME (M. Grahn, personal communication, March 18, 2020). RME stands for rapeseed methyl ester and as the name suggests it is derived from rapeseed (Merkisz et al., 2016). Additionally, other plant-based oils are suitable for production of biofuels, such as sunflower, peanuts, linseed, palm oil etcetera (Merkisz et al., 2016). DME stands for dimethyl ether, it can be produced by creating syngas from natural gas, biomass, or even organic waste (European Biofuels Technology Platform, 2011). In two synthesis steps from syngas to methanol (in the presence of a catalyst) and then by dehydrating the methanol (once again in the presence of a catalyst) DME is produced (European Biofuels Technology Platform, 2011). However, with these types of liquid fuels you still get carbon dioxide (CO_2), nitrous oxide (NO_x), Particulate matter (PM) and noise at the location were the engine is run. This may not be a problem when it comes to accounting for CO_2 emissions if biofuels are used but in large cities with large amounts of congestion the issues of combustion may remain, such as smog. An alternative that was discussed is that when it comes to short distance travelling, for example within cities electrification (for example, through batteries) is seen as a better alternative in solving the local issues (such as less NO_x, soot and smog particles). These technologies still can have a carbon footprint but at the actual "tail-pipe" of the vehicle the emissions are lower to non-existent. Additionally, for long distance travelling it was discussed that currently the best option would be to use liquid biofuels and trying to make the technologies that use liquid biofuels more efficient.

It should also be mentioned that for biofuels that are found in the European Union (EU), a directive called the Renewable Energy Directive is used to create policy that reinforces the sustainability criteria for bioenergy and what is used to create this bioenergy. In short it wishes to create a directive that supports the use of biofuels that help reduce emissions and limiting the amount of land use change needed to provide these sources (European Commission, 2020).

During the discussion it was pointed out that there are various standards that are used for fuels. For example, a standard called EN590 is used were it does not directly mention that it has to be diesel. This means that as long as a liquid has the acceptable chemical attributes and lies within the accepted range of EN590 it can be used as a substitute to diesel. Additionally, it was mentioned during the discussion that there has been greater success in finding other alternative liquids that mimic diesel like properties than petrol. There was no clear reasoning to why this is the case, but in short there is a larger variety of biofuels fit for diesel rather than petrol were the closest biofuel for petrol, is petrol with a percentage of biofuel mixed in it (for example M5 means that there is a 5% mixture of methanol in the petrol) (M. Grahn, personal communication, March 18, 2020).

Currently, when it comes to the hydrogen production, storage, distribution and use in a complete life cycle perspective it is difficult to definitely say what the overall expected emissions can be. In a simple case if the hydrogen production is coupled only and directly to a green electricity source such as a wind turbine or solar cell PV then it could be said that with those electrical generation inputs and an electrolyser then the reduction in fossil CO_2 could be the greatest. Situations that complicate this mix is if the hydrogen is still produced from an electrolyser, but it is connected both to green electrical generating sources and the grid. By being connected to the grid the type of electricity supply would affect the amount of CO_2 that the produced hydrogen would be accounted for. Furthermore, if hydrogen was chosen to be made instead with steam reforming of, for example, methane, this would most probably give/accredit the hydrogen with a CO_2 emissions value. The stated case/examples above can be for the production part of the hydrogen, when it comes to how it is consumed this could also affect the contribution to the CO_2 calculation. There are two possible ways that the hydrogen could be used. Either it could be injected into an internal combustion engine, were it would be ignited, and the expansive/explosive energy would be used to drive a piston creating useful rotational energy and heat (less useful) to drive the vehicle. In this example, it can be assumed that no CO_2 would be released from the fuel. However, due to the nature and design of a combustion engine some of the lubricating oil could leak into the combustion chamber, thus adding to the potentially overall emission of CO_2 for using hydrogen. An ideal, route could be to only generate electricity from known sources that can be verified and possibly certified of being fossil free and the hydrogen being used to produce useful energy (in this case electricity to drive an electric motor) through a fuel cell. As there is no carbon atoms found in the fuel and no oil is used in a fuel cell, the only outcome/product is expected to be water (liquid, gas and combination of both) (M. Grahn, personal communication, March 18, 2020).

In a paper from Fernández-Dacosta et al. a comparison (both cost and environmental impact) was made between hydrogen produced through steam reforming and electrolysis and CO_2 based fuels (methanol and dimethyl ether). In the paper it was concluded that the cheapest way of producing hydrogen is from steam reforming without CO_2 capture but with a similar global warming potential (GWP) of diesel and gasoline (figure 8 of the report). The most environmentally friendly way of producing hydrogen is via green electricity and electrolysis, but at a greater expense than steam reforming. When it came to the CO_2 based fuels DME and methanol without CO_2 removal have a considerable amount of GWP as well (Fernández-Dacosta et al., 2019).

In a report from Källmén et al. an interesting conclusion that was reached/agreed upon was that regardless of the emissions accounting approach, all kinds/types of HVO liquids give a decrease in GWP compared to fossil diesel. (Källmén et al., 2019). This is pointed out as the work that Renova has been doing in trying to reduce emissions from the vehicles in its fleet from diesel to HVO and the next step towards electrification is a valid and sound route.

5 Results and Discussion

Due to the size and nature of the project it was felt by the author that during each section of the analysis some discussion should also be made to help relate the project with the stated information. In this section of the report the most important results will be stated with some further discussion. Overall, in the report the possibilities of own energy supply, hydrogen production and storage units/stations, energy utilisation from the Sävenäs plant along with the emissions were analysed.

The results were that Renova has enough space for producing their own electricity from their premises to be able to supply the electrical energy needed for a HRS with a hydrogen capacity of 28 kg/day. The calculated electrical demand for the HRS being operated continuously for a year was found to be around 0.6 GWh. The electrical energy supply from Holmen itself was found to be around 1.72 GWh. In total, the theoretical electrical energy supply from the visited locations during the study visit, Holmen and the ORC units was found to be around 7.5 GWh (with the ORC configuration from Climeon AB) or 5.14 GWh (with the ORC configuration from Againity AB). Luckily, Holmen, which is the location were most vehicles, including the hydrogen refuse vehicle of Renova's fleet is found to have enough electrical supply to be able to say with confidence that there would be enough supply close-by to the HRS to meet their demand. The remainder of the locations are both spread out and far from each other (in some cases) and Holmen. In the report, distance from the supply, to the demand, or to a grid connection were not discussed/analysed in detail as it was felt that it was not applicable for a preliminary analysis.

In the case of Sävenäs, it has been identified that the plant has been worked on systematically and large improvements in energy efficiency have been made. The remaining parts of the energy that does not get utilized is to a degree bottlenecked in various ways. One problem is that the amount of district heating customers is not enough for the summer period. Had the demand been enough throughout the summer period then there would have not been any need to cool some of the district heating fluid. Furthermore, due to the environmental restrictions regarding how much water is allowed to be extracted, consumed and returned from/to the Säveån river and the allowed temperature difference between extracted and returned water are seen as limiting factors to how well the plant can be run. Changing one of these mentioned bottlenecks would allow the plant to better meet its main goal of reducing the volume of waste generated by society and recovering as much energy from it as possible. Being able to run an ORC unit to make use of some of the energy that would otherwise be vented to the atmosphere, would in a way allow the backpressure steam turbine operate more efficiently, by creating an "artificial" demand for heat. This is however, restricted by how much energy that is available from the Säveån river.

Throughout the project's work it was identified that there are not a lot of companies that offer complete turn-key hydrogen refuelling station options. From some of the companies that answered the questionnaire questions a possible size of a HRS (whose hydrogen capacities are larger than Renova's current needs) offered by them would be 67 m^2 (from Nel ASA) up to around 119 m^2 (Hydrogenics). More companies can be found in the electrolyser and/or fuel cell sector. The footprints of the various HRS were calculated and mentioned but a final placement/location at Holmen was not suggested/identified. This was done due to various reasons, varying from the analysis of Holmen itself not being done in greater detail due to the COVID-19 pandemic (advised to limit travels and interaction with many people), to the Google Maps images not being seen as up to date for a remote analysis of the location. Instead, by at least having calculated/identified the size needed this could be useful for later on in the project if it is decided to be continued.

The expected tail-pipe emissions from running the hydrogen driven refuse collector within cities and its intended route would have a very small global warming potential compared to the combustion engine variant. An actual value was not calculated to how much the expected emission reductions could be, primarily due to the fact that a complete cradle to grave emissions report, were not only the tail-pipe emissions from the actual vehicle but also the raw material extraction, production (vehicle, fuel, HRS equipment) and decommissioning of them would have been a complete report on its own (the time and detail needed would validated an project solely focused on that).

Regarding the economic aspects a partial calculation was done regarding the electricity cost and cited the complete costs at the pump. The calculated cost was found to be around 1.87- 2.35 €/kg (assuming only the electricity cost) and the expected cost of 10-12 €/kg from Fronius HRS unit. These values indicate that decentralised small-scale hydrogen production is possible but at a higher price. If the goal is to only procure the fuel at the lowest price the result would be different (most probably buying more emission burdened fuel from industrial scale productions). However, if guarantee of supply, clear emission burdens from own production is valued then decentralised green hydrogen production is a great alternative. Also, the high cost difference between reformed and green hydrogen is believed by the author to be primarily due to the absence of economies of scale from the green hydrogen supplying companies. They are currently in the early commercialisation stages, meaning that prices should continue to fall hopefully bringing green hydrogen to a lower more competitive cost.

6 Conclusions

To begin with, it is felt that the preliminary analysis of the hydrogen production and storage opportunities at Renova has been successful. Available areas for green electricity production by using photovoltaic cells within the boundaries of Renova's premises have been identified. Possibilities for electricity generation from recovering some of the presently cooled district heat at the Sävenäs plant using ORC technologies/solutions have been identified. Furthermore, the Sävenäs plant can be seen as being too large for the district heating network that it serves, as the demand during the summer is lower than the plants heat output (not enough customers year-round to meet output). Cooling can be seen as being the bottleneck during the summer to allow the plant to operate at maximum capacity and output (not enough cooling available). With the proposed ORC unit configurations an expected increase in cooling capacity would be the result as well as energy recovered, and useful electricity produced. Also, due to the size of the project, not all steps need to be fully utilised or developed for another part to work. For example, as electricity is used to power the electrolyser it does not mean that excess electricity cannot be utilised for another part. Also, the solar cells section and Sävenäs ORC can be seen as independent to each other and to the hydrogen production section. This means that if it is desired, these sections could be further developed on their own (e.g. try to maximise electrical energy production).

Knowing that hydrogen refuelling stations (HRS) are planned to be opened quite soon within the Gothenburg region, were one is planned to be available from July-August 2020, less than two-three months from when the report is being written. Due to the expected timeframe of planning and implementing and operating the hydrogen refuelling station it would be advisable to initially wait and see how the hydrogen truck performs and if it meets the expected requirements, and in the meantime refuel from other HRS. If the requirements are met by the truck and the planned 30 trucks until 2030 is still on track and the desire to own and operate an HRS still exists by Renova then this report can be used as an initial analysis. Furthermore, this is suggested as it is identified that the refuelling of a hydrogen refuse collector via electrolysing water to produce hydrogen is not within the core business plan of Renova. Instead, the hydrogen refuse collector itself falls perfectly in-line with Renova's values. A hydrogen powered truck is seen as being the correct next step in collecting refuse in an environmentally, and sustainable manner as possible.

7 Future work

In this section some possible future plans will be suggested and discussed. If some solar cells are planned to be installed, then it is suggested to read through the solar cell guide from the Energy authority of Sweden direct towards companies. Anna Derneryd who is a project manager at the regional energy agency of West Sweden was very helpful in answering the authors various questions and providing a link to the mentioned solar cells guide. Some of the work has already been done in the report which are mentioned in the guide steps, for example, if a roof is planned to be rebuilt or newly renovated. Furthermore, something of interest that is mentioned in the solar cell guide is that the subsidies that have been used to promote solar cell installations will be stopped after the 31st of December 2020. Additionally, the maximum subsidy allowed is around 20% and solar cell installations should be finished before the 31st of December to be eligible for the subsidy (Energimyndighetens webbshop, 2020).

If a HRS is planned a possible second step would be to visit other HRS that are similar to Renova's case. For example, in Mariestad the refuelling station there uses some solar cells to generate electricity for an onsite electrolyser and HRS. The municipality was contacted multiple times (via email and phone calls) but never got back with any information.

A possible next step, for the ORC plant at Sävenäs could be, to make a so-called pinch rule analysis to make sure that cooling and heating takes place in the ideal/correct place (possibly an updated one accounting for all heat-pumps available). With the pinch rule analysis, a limit or boundary temperature can be found were in short cooling should take place below the pinch, heating above the pinch and do not transfer heat through the pinch so as not to violate the pinch rule. Possibly, the pinch rule analysis would help give an indication at what level the technoeconomic equilibrium would be for the ORC unit size.

As in the case of the Fronius Solhub station a 4th case of a possible design of a hydrogen refuelling station could be that it can also offer grid balancing and seasonal storage by having a fuel cell that could be used to produce electricity at the refuelling station (offering an extra feature that could possibly generate income for the company). Figure 49 below, shows how the HRS with grid balancing capability could look.

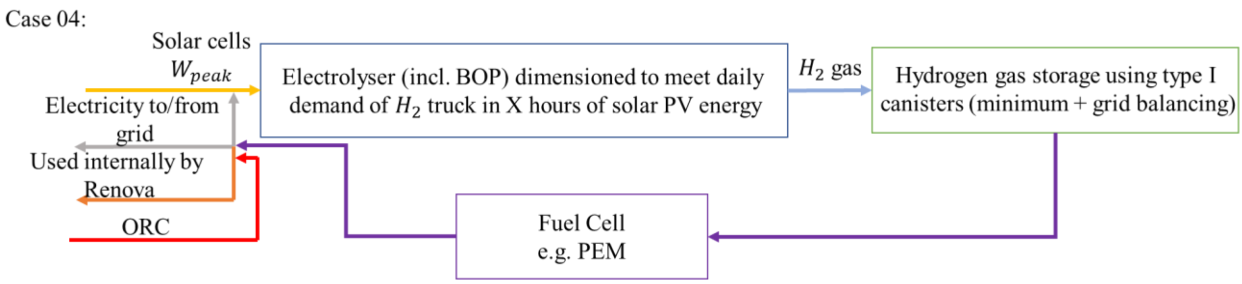


Figure 49: Possible future design of a HRS at Renova that also offers grid balancing through a fuel cell and power electronics.

Furthermore, in the report primarily green hydrogen has been investigated using electrolysers. This in short, does not really fit in the core of Renova's working area. A possibility could be to investigate high temperature gasification of for example, waste to generate hydrogen. This would allow for both parts of the company, energy recovery and logistics to benefit from this. The energy section of the company would produce the hydrogen gas and the logistics part would have the demand. This could possibly fit much better within the company's main goals. Such an example was mentioned in the news outlet FuelCellsWorks were a company SGH2 mention that they are planning to build such a plant (FuelCellsWorks, 2020).

In the report, the primary method of storing hydrogen was in compressed gas form in canisters (usually heavy, metallic type I canisters). If there was a desire of being able to transport the fuel to another location to refuel other vehicles it would be quite cumbersome to do in this state. Other, methods of storing the fuel could be investigated in the future. For example, if a liquid could be used to transport the hydrogen, release it to get clean hydrogen gas and compressed to refuel onboard the vehicle would be a win-win situation as this could be transported with normal tankers that are used today for petroleum products (utilizing existing infrastructure).

In the report, it was mentioned that biogas could be used to produce hydrogen but requires a lot of cleaning steps. A company called Helbio S.A in Greece was found that offer such a solution but this was not analysed further in this report as Renova does not operate any biogas plants (only prepares the slurries at Marieholm) (HELBIO S.A, n.d.). Additionally, Helbio is part of a Swedish company called Metacon AB whose goal is to commercialise large and small energy systems for the production of electricity, heat and hydrogen (Metacon AB, n.d.)

Finally, if more actors are brought onboard a project in collaboration with Renova (basically increasing the projects boundaries) this would allow for even more opportunities to implement some of the analysed parts. For example, if Gothenburg Energi, could be involved with the district heating and ORC units then a better location could be chosen to create this "artificial" demand in the summer. For example, if there is space at Holmen, the Göta Älv river could be used as the cold medium thus increasing the possible size of the unit (because Göta Älv is much bigger that the Säveån river). Furthermore, when it comes to the solar cells and continuous available rooftops, a larger complex (of interconnected rooftops) can be seen in figure 50 below.

Figure 50: Rödingen balling station and adjacent connected buildings showing potential for more rooftop areas for solar PV's available. Source of image: (Google Earth, n.d.-c).

Not all areas may be applicable for solar cell installations as for example the harsh environment at Tagene, may need some extra planning, both in installation, design, but also may also require more frequent cleaning of the solar surfaces. Additionally, when looking at the buildings that were visited by Camilla Svensson and the author during the field trip, it was noted that a row of buildings looked continuously connected to the Rödingen buildings. The other buildings are not part of Renova, but they too have great solar irradiation and low roof inclination making them also good candidates for installing solar cells (continuous rooftops assumed to lower installation costs).

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Appendix A

This section of the appendix explains in greater detail the remainder of the vehicles presented in figure 2. Figure 51 below shows the hook lift truck unloaded and loaded along with a trailer.

Figure 51: Hook lift tuck unloaded and loaded along with loaded trailer (H. Zackrisson personal communication, April 27, 2020).

The unloaded hook lift truck in figure 51 has an approximate length and width of 7.9 m and 2.55 m respectively, while the loaded truck has a total length of around 25 m and total weight around 30 tons (H. Zackrisson personal communication, March 4, 2020). Once again this is an illustration of the maximum limits of this type of vehicle, some have for example a lower total weight. The hook lift truck on average consumes 55 L/100km and drives approximately 4200 km/month (H. Zackrisson personal communication, March 4, 2020). As the refuse collector (including refuse collector 2 slots) and hook lift types make up more than 50% of the total number of vehicles owned, the level of detail for the other type of vehicles in the report are not described to the same degree. Figure 52 below, shows an unloaded skip loader.

Figure 52: Skip loader unloaded (H. Zackrisson personal communication, April 27, 2020).

The skip loader/dumper shown in figure 52 has an approximate length and width of 6.3/6.6 m and 2.55 m respectively with a total weight of 18 tons (H. Zackrisson personal communication, April 27, 2020). While another configuration of the same vehicle type can have a total weight of 30 tons (H. Zackrisson personal communication, March 4, 2020). Figure 53 shows the electric refuse truck that was put into use in 2019.

Figure 53: Electric refuse truck that was put in use in 2018 (H. Zackrisson personal communication, March 5, 2020).

The electric refuse truck has an approximate range of 70 km/charge, weighs around 18 tons and can collect around 8.5-ton of waste (H. Zackrisson personal communication, March 5, 2020). Figure 54 below shows a typical crane truck.

Figure 54: Crane mounted truck (H. Zackrisson personal communication, April 27, 2020).

The crane mounted truck shown in figure 54 has an approximate length and width of 9.8 m and 2.55 m respectively with a total weight of around 26 tons (H. Zackrisson personal communication, April 27, 2020). Figure 55 below shows what a typical truck mounted crane with refuse collector looks like.

Figure 55: Truck mounted crane with refuse collector (H. Zackrisson personal communication, April 27, 2020).

The truck mounted crane with refuse collector shown in figure 55 works by using the crane to lift larger bins (such as recycling bins) and dumping the content of the bins over the opening at the back of the waste compressor/compactor. An approximate length and width of such a truck lies around 10 m and 2.56 m respectively, with a total weight of 26.5 tons (H. Zackrisson personal communication, April 27, 2020). Figure 56 below shows a typical van that is below (left side of figure) and above 3.5 tons (right side of figure).

Figure 56: Van <3.5 ton (left) and van >3.5 ton (right) (H. Zackrisson personal communication, April 27, 2020).

Figure 57 below shows a typical sludge-truck.

Figure 57: Typical sludge-truck (H. Zackrisson personal communication, April 27, 2020).

The weight configuration of the same vehicle type varies but the maximum total weight lies around 29 tons (H. Zackrisson personal communication, March 4, 2020). Figure 58 below shows a typical vacuum cleaner truck.

Figure 58: Vacuum cleaner truck (H. Zackrisson personal communication, April 27, 2020).

As the name mentions the vacuum cleaner truck operates with a vacuum, and an application area could for example cleaning water drains from leaves and other foreign objects. Figure 59 below shows a typical garbage bin cleaning truck.

Figure 59: Garbage bin cleaning truck (H. Zackrisson personal communication, April 27, 2020).

As the name suggest a garbage bin cleaning truck, is a truck that can clean garbage bins, for example if a garbage bin smells, then this truck can be used to clean the bin and remove the odours. The approximate length and width of the truck lies around 7.7 m and 2.4 m respectively, while a total weight could be around 12 tons (H. Zackrisson personal communication, April 27, 2020). Figure 60 below shows a typical front loader refuse truck.

Figure 60: Front loader refuse truck (H. Zackrisson personal communication, April 27, 2020).

The front loader truck operates by picking larger recycling bins and lifting it above the cab and tipping the content in the back. An approximate length and width of the front loader refuse truck lies around 9.5 m and 2.55 m respectively while having a total weight of 33 tons (H. Zackrisson personal communication, April 27, 2020). Figure 61 below shows a typical truck tractor pulling a trailer.

Figure 61: Truck tractor with trailer (H. Zackrisson personal communication, April 27, 2020).

An example where the truck tractor pulling a trailer is used by Renova, is when the bottom ash (also called slag) is transported from the Sävenäs plant to Tagene landfill. This truck configuration can load approximately 30 tons (H. Zackrisson personal communication, April 27, 2020).

Only 14 out of 17 types of vehicles used by Renova are depicted here. One of the remaining three types of vehicles is the truck mounted crane with hook lift which is a combination of figure 51 & figure 54. The second to last type is the demountable truck which is also called a “chameleon” truck as it can change its attachment to meet the desired needs. Finally, the last type of vehicle is the flatbed truck < 3.5 ton which looks like the van on the left from figure 56, but instead of a box on the back of it, it has a flatbed.

Appendix B

Questions about hydrogen canisters/cylinders

Disclaimer/ note from author of thesis work: The thesis work that is done at Chalmers University of Technology is intended to be published. This means, if the company chooses to participate, they should be aware that unless agreed upon by the author and the company, the data provided may be published.
Additionally, if any question(s) is regarded to be too sensitive by all means, the company can skip answering said question(s).

- Does the company wish to be referred to anonymously in the thesis report? (For example, Company A requires x m^2 of space for a supply of hydrogen to meet the daily demand) (Or even an answer such as "No, except for the prices/cost." works as well)

  "Bought Hydrogen"

- From my understanding the company can provide hydrogen canisters in "pallet" form. What is meant by pallet form, is that, if a large quantity of hydrogen is needed, instead of a single cylinder being delivered, a larger unit containing multiple cylinders can be supplied. Have I understood this correctly?
- Firstly, I was wondering what are the usual sizes of these containers/pallets? (For example, a pallet of **x** m^2 contains **y** number of cylinders (of volume **z** litres at **v** bar))
- Additionally, the expected hydrogen demand per day is around 28 kg/day at around 350 bar. How many pallets would be needed to satisfy this demand? (Can assume/imagine that the customer has a compressor to increase hydrogen pressure from that of the cylinders to 350 bar)
- If this demand is taking place at a location within Gothenburg, Sweden, approximately what would the expected cost be? (possibly including the transportation of the pallets to and from the customer location)

  "Own hydrogen production with bought/rented storage"

- If the customer was producing his/her own hydrogen from an electrolyser could the customer buy or rent multiple pallets to store the produced hydrogen from said company?
- What sizes of containers/pallets can be ordered by the customer? (By sizes this refers to the m^2 area of the pallet, the number of cylinders per pallet, the type of cylinder (type I-IV), the capacity of the cylinder (L), and the pressure allowed (bar))
- What would the expected price be for the customer to receive pallets with empty canisters that he/she will fill with own produced hydrogen to meet a daily demand of 28 kg/day?

  "General"

- Are there any safety requirements for storing such pallets, canisters on site?
  - For example, only in open spaces, away from heat sources?
  - A certain distance is needed between the hydrogen storage and the "consumption" area? E.g. needs to be 20 m away from the compressor?
  - A special certificate is needed to be able to store such gases on site?

Appendix C

Question to hydrogen producing company

Disclaimer/ note from author of thesis work: The thesis work that is done at Chalmers University of Technology is intended to be published. This means, if the company chooses to participate, they should be aware that unless agreed upon by the author and the company, the data provided may be published.
Additionally, if any question(s) is regarded to be too sensitive by all means, the company can skip answering said question(s).

- Does the company wish to be referred to anonymously in the thesis report? (For example, Company A requires x kWh of energy per kg hydrogen produced at 350 bar) (Or even an answer such as “No, except for the prices/cost.” works as well)
- For a demand of 28 kg a day and a refuelling pressure of 350 bars does the company provide such a complete, turnkey unit (i.e. electrolyser, compressor, storage, dryer etc.)?
- What would be the requirements from the customer’s side to accommodate the unit?
    - Water quality?
    - Electricity demand voltage/current/power?
    - Space, area?
    - Anything else?
- What type of electrolyser is suggested/provided by the company for this application?
    - Proton exchange membrane (PEM)
    - Alkaline
        - What type of alkaline electrolyte is used? E.g. KOH etc.
- Approximately how much is the power/energy distribution in the complete unit? (For example, 1 kWh/h of electricity, 85% used for electrolysis, 10% compression, 15% to remaining components.)
- What would be the expected consumption of the unit to provide 28 kg_H_2/day? (For example, energy [kWh], water [L] etc.)
- What kind of storage method is used to store the hydrogen that is produced from the electrolyser? (For example, metal gas canisters, metal hydride containers etc.)
- If the company chooses to produce its electricity from photovoltaic cells, can it be expected that the bottle neck of the system could be in having enough production and storing capacity. Does the company provide a unit that works within a range? (For example, 28-35 kg_H2/day.)
- What is the overall efficiency of the system in terms of Lower Heating Value (LHV) at a specific load? (e.g. LHV efficiency at 28kg_H2/day at 350 bar.)
- Has the company provided such a solution before, to another customer?
    - If yes, any articles, publications that you could provide?
- This might be a sensitive question, but is there in any way a possibility of getting a ballpark estimate for how much, such a unit would cost? (for example, could be as rough as, 4, 5, 6, 7 figures in [€].)
- If the company that requires such a unit decided to acquire such a unit from you today what would the estimated time be, for taking delivery of the complete unit? (for example, within 90 days would have unit delivered, installed, producing hydrogen and being able to refuel the trucks.)

- Is there anything unique that your company can offer that sets you apart from your competitors? (for example, 24/7 on-site customer support if needed, software that allows the customer to see how much is currently being produced and consumed, training for company personnel, safety training etc.)
- If there are any other points that have not been covered by the questions that you feel are relevant, please do give them. For example, if you can suggest a configuration that provides at least the desired demand and helps in allowing the unit to accommodate an increase in demand (if the company chooses to increase its number of H2 vehicles) please do.
- Additionally, can the unit be adapted to provide 700 bar of hydrogen as well?
  - If yes, any major changes that are needed to be made? (e.g. space, electricity consumption etc.)
  - If no, what unit could provide both solutions and meet the 28 kg_H2/day?
  - What would the implications be to the cost (if possible, to answer)?

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