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Energy Concepts for Energy Hubs with Integrated Hydrogen Refuelling Station (HRS)

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“You never fail until you stop trying.” — Albert Einstein

Abstract

As the world is emphasizing the urgent of the green energy transition, hydrogen undoubtedly is one of the best substitutions choices of as it can be produced by many robust and innovative technologies that available in the world. The recorded hydrogen activities in the adaptation of hydrogen as the new fuel sources in Norway remains slow , however, several major developments had recently been looked into. A Norwegians grocery wholesaler and transport company is concerned about the environmental issue and aimed to achieve zero emission within the organization. The company had started to invest in many renewable energy and clean transportation fuel development projects. Zero emission vehicles that could travel long distance is desired in order to achieve the zero emission on the road. An electrical car is unfortunately not favourable in this case and leads to hydrogen vehicles would be the only option left. A hydrogen refuelling station is important to ensure the vehicles are charged all the time. Hence, the great potential of new hydrogen energy become the driver of this study to find out the best scenario that will accelerate the hydrogen market in Norway.

Taking the company situation as inspiration, an energy hub approach is utilized to integrated all the energy supply and demands. The boundary of this study was initially unclear. In order to minimize the freedom of changes and discussion, the project framework has been defined. Several technical arguments had been discussed to find out the optimum design for the energy hub. The different case study has been described and the particular model has been simulated in the steady-state conditions, using HySys software. Based on the results, the system designed is optimized and modified. The overall flow diagram of the designed system was then established.

Besides, an extended dynamic simulation that integrated the supermarket heat pump system and the hydrogen refuelling station cooling has been developed in Dymola. The different demand for hydrogen refuelling had been tested to study on the cooling demands requirements.

Extended reviews had been done on the equipment that is available in the market. The energy hub designed, is based on the equipment available on the industrial scale. Hence, this system design is technically feasible and ready for development.

Preface

The basis for this project originally stemmed from my passion for developing a strong technical knowledge on the energy and low temperature applications. This master thesis project formulated the basics to drive a new energy market and the challenges associated. The energy hub approach that manage the interfaces between different types of energy would minimize the import of energy, maximize the waste heat recovery and provide the optimum energy design solution.

I would like to express my utmost gratitude to my supervisor, professor Dr.ing Armin Hafner and my co-supervisor Christian Schlemminger for their unwavering support, encouragement and excellent guidance throughout this project.

I would also like to thank my family and friends who gave their best support and encouragement throughout my study at NTNU.

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Abbreviations

HRS = Hydrogen Refuelling Station
APRR = Average Pressure Ramp Rate
GHG = Greenhouse Gaseous
UN = United Nation
IPCC = The Intergovernmental Panel on Climate Change
PEM = Polymer Electrolyte Membrane
PFD = Process Flow Diagram
SAE = Society of Automotive Engineers
TIR = Technical information report
DHW = District Heating Water
LT = Low Temperature
LLT = Low Low Temperature

Chapter 1

Introduction

1.1 Background

Discussion on the hydrogen as the emission-free fuel alternative is getting more attention again due to the uncontrolled speed on the climate changes. Equinor had recently published the ”Energy Perspectives 2019”. One of the main conclusions is mentioning 50% of the electricity must come from the sun and wind, and the use of coal must be phased out, in order to achieve the global warming below 2 °C by the year of 2050. (Equinor, 2019) Recently, there are more hydrogen activities had been initiated in the world including the Japan ambitious move to bring in a fleet of fuel cell buses for Tokyo 2020 Olympics and the Korean launching of the first mobile liquid hydrogen dispensing truck.

Hydrogen, which is mostly use only as an energy carrier in the past, was actually the most abundant elements on the earth. The technologies to harvest the hydrogen has not getting too much attention compared to oil and gas in the recent decades and lead to today’s situation of lacking advanced technologies for hydrogen energy harvesting compare to hydrocarbon. The interest of a Norwegians grocery wholesaler and transport company on renewable and hydrogen energy is driving the hydrogen market in Norway.

An energy hub is design to supply the energy requirements throughout the year to its surrounded amenities. Due to the fluctuation of weather and usage conditions, it can be challenging to accommodate the energy supply and it is impossible to design everything on its peak demands. Hence, the aim of this project is to find out the optimal strategies, system design, configuration and equipment sizing which gives the higher performance with lower cost. This will be done by comparing the difference case studies and to find out the most suitable design.

This project work aims to gain the knowledge on existing hydrogen technologies and develop an energy hub concept with a simplified model that will be use for the dynamic modelling and technical evaluation. The objective of this integrated system is to lower down the capital cost by avoiding investment on two duplicated heat pump system for both supermarket and HRS. Besides, by integrating the users in both system, the operating cost due to energy use can also be lowered down after the heat pump integration. A dynamic simulation model that consists of all the components in the system will be developed to investigate the potential for using the waste heat to cover the energy demand.

1.2 Introduction

In the next chapter, the existing project, technologies and the HRS designed will be discussed to get an overview on the market conditions. The available hydrogen production, storage, refuelling technologies will be reviewed and discussed based on all equipment that are included in the enrgy hub. Several comparison on the different alternatives available will be discussed. Besides, the Norway transportation and and energy system statistics will be studied . The data that collected through the reviews will be recorded, to design the vehicle roll-out and refuelling scenario. These scenarios is critical to give the boundary of this study and to make the project realistic.

The project envelope will be defined in chapter 3. Most of the equipment that are consisted in the energy hub will be discussed. The defined design boundary will reduce the project freedom drastically. From there, the heating demands, cooling demands and waste heat available within the energy hub could be identify.

Several arguments over the system design alternatives will be studied and optimised in chapter 4. The alternatives will be studied from the technical aspects, and the best alternative will be picked. The system design will then be modified. The design of the baseline concept that had been developed will be explained in chapter 4.

In chapter 5, several softwares i.e Dymola, HySys that utilized in this project will be discussed. The HySys software will be used to run the steady state simulation, while the Dymola will be used for dynamic simulation purpose. The simulation model and results will be discussed in chapter 5.

The work done will then be concluded in the following chapter and some further work will be suggested. The open item that need to be taken care in the next phase will also be addressed.

1.3 Problem Description

Today's HRS are either producing hydrogen on-site or are supplied externally. Both cases are standalone systems connected to the power grid only. On-site hydrogen production using electrolysis produces surplus heat from the electrolysis, compression and cooling that might be taken up in an integrated energy hub. The temperature range for the electrolyser and the inter-cooling of the hydrogen compression is 30 - $150\,°\mathrm{C}$, representing up to 40% of the energy losses for the on-site production by electrolysis. A cooling capacity at temperatures of $-40\,°\mathrm{C}$ is required to allow fast filling adding 5-10% heat losses at ambient operational temperature levels.

The basic idea of the energy hub is an integrated refrigeration system, where the refrigeration provides surplus heating and cooling demands for the nearby buildings. It also delivers the cooling demands required within the HRS. The energy hub may be connected to a local thermal grid, if necessary, too.

The aim of the master thesis work is to gain new knowledge that could invoke technological development and lower capital costs due to surplus heat recovery with integrated on-site HRS, develop the energy flow with the simulation tool, and enabling the evaluation of different scenario concepts.

Chapter 2

Literature Review

2.1 Existing Relevant Projects and Case Studies

The concept to integrate the hydrogen technology with renewable energy is not something new. Back in earlier 20s, several smaller scale project had been realized in Europe and in Norway. The scale of renewable farm could be significant. Unfortunately, most of the built solar or hydrogen system are in small scale until recent years. Also, these studies that had been done emphasized a lot on the hydrogen technology design instead of the energy efficiency and utilization. This might because lacking of the large scale project application datas. (Ghosh et al., 2003) (Øystein et al., 2010)

2.1.1 The Solar/Hydrogen Refuelling Station System - ASKO

The most recent hydrogen development in Norway that are closed to an energy hub concept, would be the ASKO project. ASKO, the norwegian largest grocery wholesaler and transport company, owns 13 regional warehouses, 8 stores, 2 central warehouses and one consolidation terminal (Vestby), is also very concerned about the environmental issues. The organisation owned more than 600 trucks than running on the road everyday. Electricity and hydrogen fuel vehicles are the only option in order to achieve zero emmision on the road. The energy dense hydrogen fuel would able the vehicles travel for a longer distance with zero emission while the electrical car is more suitable for short distance urban distribution.

ASKO is aiming to achieve climate neutral with renewable energy generation by 2020. Hence the organization is very active with wind, solar energy and the potential of hydrogen energy these years. There are several projects are under development, such as to get the rooftop solar powered hydrogen production and hydrogen refuelling station by Nel technology (C-150) in Trondheim at the end of 2019. This would be a very important milestone for ASKO because this project in Trondheim would be the pilot project. If the project is successful, several more similar facilities will be potentially established. The hydrogen production unit will combined the C-150 containerized from NEL Hydrogen Solutions to deliver 300 kg hydrogen per day.

Though, generates energy from renewable sources i.e solar and wind is not something new to ASKO. Up to the year of 2017, ASKO owned a total of 90,000m^2 solar power energy generation, which is equivalent to approximately 15% of the organization consumptions. The ASKO store in Vestby has the solar panel of 30,000m^2, which the generated power is also connected to the electrical car charging ports. The carport allows up to 10 cars charging at the same time. (Nel ASA, 2016) (NorgesGruppen, 2019) (Jannicke Nilsen, 2016)

The **Table. 2.1** below shows the potential parameters of key components of the ASKO project in Trondheim.

Key Component	**Specification**
Alkaline Electrolyser	50-150 Nm^3/h
No, of dispenser	3 (2x350 bar; 1x700bar)

Table 2.1: Potential Key components for the ASKO project in Trondheim

2.1.2 The wind/hydrogen demonstration system - Norway

One of the earliest and promising hydrogen production project in Norway is carried out by StatoilHydro (formally known as Norsk Hydro) and Enercon in Utsira, Norway. The Utsira project are design to provided the energy to 10 households with the energy consumption of approximately 200MWh/year in a remote area up to 2-3days. The success of this project had provided the great insights and benchmark for a standalone renewable-hydrogen system at off grid location. The study on the system performance over a four years duration had concluded that more upgrading work will need to be done based on the existing system design in order to achieve the independent energy supply at the remote area. The improvement that can be done based on the study are: increasing the hydrogen storage capacity (can be done directly or indirectly by increasing the hydrogen pressure in order to increase the storage density); or generally, increase the efficiency. The Utsira project had initially utilized the hygrogen generator for power production, which gave a challenging situation to achieve a high efficiency system. The study had concluded that the overall energy efficiency would have doubled by simply replace the hydrogen generator set with fuel cell system (Øystein et al., 2010). The energy system flow diagram is as the **Figure. 2.1** and the list of key components can be found in the **Table.2.2**.

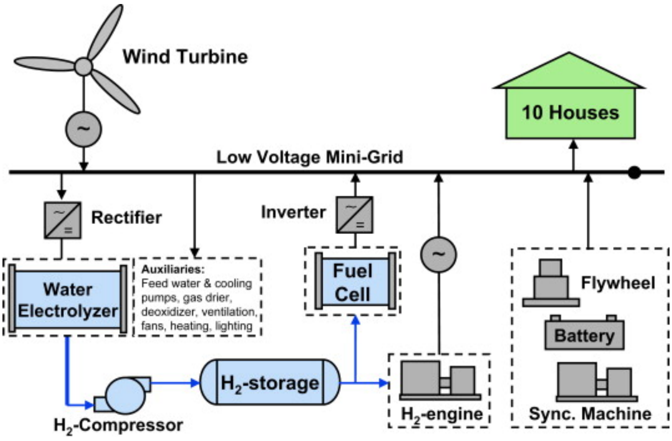


Figure 2.1: Simplified Schematic Diagram of the Project (Øystein et al., 2010)

*A hydrogen combustion engine that generate power from the stored hydrogen with the wind turbine do not have sufficient production to supply for the local demand.

Key Component	**Specification**
Electrolyser	10 Nm^3/h, 50 kW
Hydrogen storage	2400 Nm^3 (12m^3), 200 bar
Hydrogen compressor	5.5 kW
Hydrogen generator*	55 kW
Wind Turbine	2 x 600 kW (N + 1)
Fuel cell	10 kW

Table 2.2: Available parameters for key components from the Utsira project

2.1.3 Integrating Hydrogen Technology with wind power - UK

Regarding the integration of hydrogen production with wind power, a field operational were studied based on the built system in order to share the experience. In a remote island in the north of Scottish mainland, the hydrogen energy is stored during the low energy demand and used it when the energy demand is exceeding the production. It is called the PURE project that collaborated between the Robert Gordon University and the UK department of Trade and Industry. The study concluded that by integrating the hydrogen production module to the renewable plant, there is a 18% increase of the available total energy produced, which equivalent to 21MWh per annum. Besides, by implementing this new system, the on-demand heating system can be integrated and removed. together with other implementation like improvement in the building insulation, the heating on-demand heating requirement are decreased substantially by 55%. A further reduction in annual energy consumption is also expected to be reduced by 20%. (R.Gazey et al., 2006)

The given specifications of the key components in PURE project were recorded in **Table. 2.3** and the simplified schematic of the energy system could be read from figure **Figure. 2.2** .

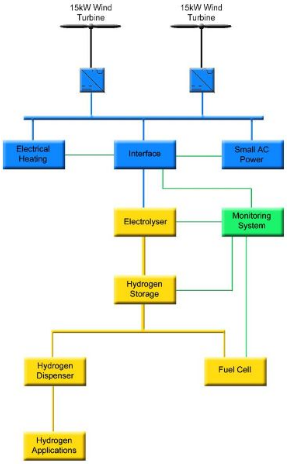


Figure 2.2: Simplified Schematic Diagram of the Energy System of PURE project (R.Gazey et al., 2006)

Key Component	**Specification**
Electrolyser	3.55 Nm^3/h
Wind Turbine	2 x 15 kW
Fuel cell*	5 kW

Table 2.3: Available parameters from the PURE project

* The fuel cell produce energy from the hydrogen generated from the electrolyser and convert ti direct current with a inverter.

2.1.4 Other Relevant Projects

Kiwi, the Scandinavian supermarket chain which owned more than 600 retail outlets in Norway, has done a ambitious move to achieve the 100% green store solution. The new Kiwi store in Auli, Norway features a 1300 m^2 solar panel on the roof, transcritical CO_2 heat pump, capacity for for electric car fast charging station, and the 200m deep energy wells to store surplus heat that will be using as the energy source for the heat pump to heat up the store. The store is expected achieve CO_2 neutral, and to save up more than 50% electricity consumption based on the theoretical assumptions on paper. (Tekniske Nyheter, 2014) (Danfoss, 2014)

There are also a few more related projects that are recently under development. Among these project, majority are planned/studied to couple the hydrogen facilities to wind energy. A lot of them are having an electrolyser to generate hydrogen for storage or electricity generation, but most of them were in small scale.(Dutton et al., 2000) (Agbossou et al., 2001)

2.2 Energy Hub

An energy hub is referring to a stand alone integrated energy system that are managed and standardized to provide optimal power flow (i.e electricity and thermal energy) from multiple energy sources to the nearby premises. The size of the energy hub is depends on the consumption of nearby building based on the weather conditions. An energy hub can be operated to have its own ability to produce energy, or getting supply from the grid. A prototype of a smart energy hub that tackle the communication between the source and users had been successfully carried out. The authors segregated the loads into different level and manage the information through an algorithm. The basic idea behind the control system is dealing with the intermittent characteristic of the energy sources and coordinate between the supply, battery and loads. A power prediction is made based on the real time information from a short term weather forecast so a peak load shifting algorithm could be carried out for a more effective energy input and output management. At the circumstances of demand is higher than the load produced, load shedding procedures will be carried out in order to provide a longer operating time to the critical loads. The prototype made passed the function test based on the design and operated in a stable and reliable condition on both standalone and connected to grid mode. (Birkeland, 2018)

2.3 Hydrogen Refuelling Station Designs

When a vehicle connects to the dispenser of the hydrogen refuelling station, the vehicle starts to communicate with the refuelling station. The pressure in the vehicle tank will be measure prior to the refuelling station to determine the refuelling rate. The refuelling process stops when the vehicles tank pressure achieved the target pressure. The hydrogen temperature is potentially increase during the refuelling process due to its reverse Joule Thomson characteristics. In order to achieve the refuelling rate within the time frame, cooling of the hydrogen is necessary.

Table. 2.4 shows the design conditions of the hydrogen refuelling station discharge conditions in accordance to the protocol SAE TIR J2601 that established after a series of safety and risk assessment had been carried out. The protocol provided the refuelling guidelines for different design of hydrogen refuelling station of the 4 temperature ratings and 2 pressure ratings.

Type	**Pressure [bar]**	**Temperature [C]**
A70	700	-40
A35	350	-40
B70	700	-20
B35	350	-20
C35	350	0
D35	350	Ambient

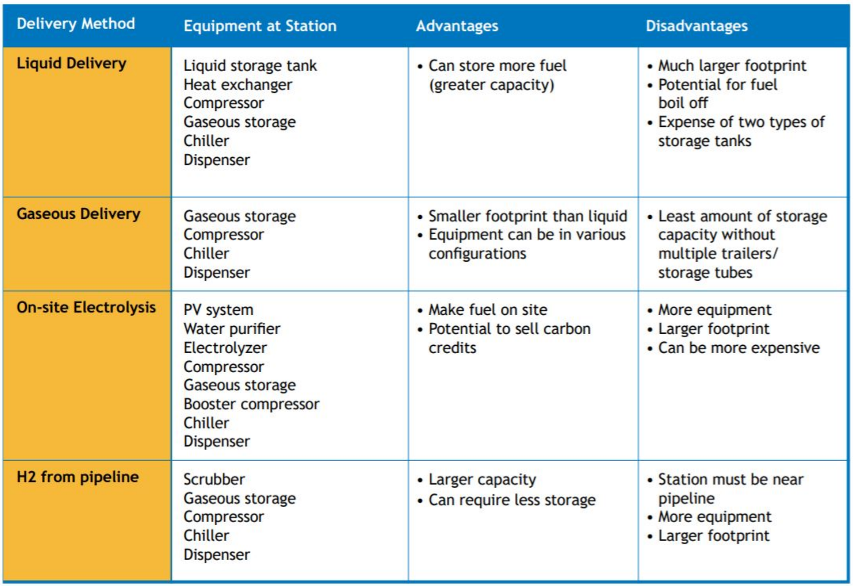
Table 2.4: Type of Hydrogen Refuelling Stations(Rothuizen and Elmegaard, 2013)

Most of the recent hydrogen refuelling station projects are mostly accommodate both 350bar and 700bar fuelling ability. The hydrogen gas usually stored in the storage tank at a very high pressure. When the dispenser nozzle is connected to the vehicle, hydrogen start to discharge from the storage tank to the vehicle hydrogen tank. The huge difference in pressure forced the mass flow towards the vehicle's hydrogen tank until the pressure get balanced off, but the hydrogen flow rate could be controlled by a reduction valve.

The overall hydrogen refuelling station designs and it's efficiency are very much depends on the hydrogen source delivered, the storage system design and the car fuelling design. For it's storage, hydrogen refuelling station generally have the design of having the hydrogen source delivered in liquid, delivered as a gas, produced hydrogen on site or hydrogen withdrawal from hydrogen pipeline. Besides, the hydrogen refuelling station can be classified in two design groups, which is the liquid hydrogen storage system and the hydrogen gas storage system. While and the downstream of the hydrogen refuelling station, the filling design can further be differentiated to booster filling method and buffer filling method.

2.3.1 Hydrogen Supply Delivery Method

The hydrogen refuelling station is equipped with a station hydrogen storage tank that use to store the compressed hydrogen and discharge to the car through the dispenser on demand. The hydrogen can be delivered to the station storage tank in many ways. Figure 2.3 shows that the comparison of the different delivery method of hydrogen to the station storage tank. The fundamentals equipment, advantages and disadvantages for each delivery system had also been listed.



Delivery Method	Equipment at Station	Advantages	Disadvantages
Liquid Delivery	Liquid storage tank Heat exchanger Compressor Gaseous storage Chiller Dispenser	• Can store more fuel (greater capacity)	• Much larger footprint • Potential for fuel boil off • Expense of two types of storage tanks
Gaseous Delivery	Gaseous storage Compressor Chiller Dispenser	• Smaller footprint than liquid • Equipment can be in various configurations	• Least amount of storage capacity without multiple trailers/ storage tubes
On-site Electrolysis	PV system Water purifier Electrolyzer Compressor Gaseous storage Booster compressor Chiller Dispenser	• Make fuel on site • Potential to sell carbon credits	• More equipment • Larger footprint • Can be more expensive
H2 from pipeline	Scrubber Gaseous storage Compressor Chiller Dispenser	• Larger capacity • Can require less storage	• Station must be near pipeline • More equipment • Larger footprint

Figure 2.3: Comparison on different Hydrogen Station Configurations(California Fuel Cell Partnership, 2016)

For most of the delivery method, hydrogen comes from natural gas except the electrolysis method. Hydrogen as the byproduct of the methane reformation is usually produced at the central facility and delivered in different method, like hydrogen pipeline, deliver as gas or liquefy and deliver in liquid form.

There is still an argument on the hydrogen as the clean energy sources as the process of the hydrogen production still creates carbon emission. This issue can however be easily tackled by producing the hydrogen from solar and wind energy by the water decomposition using an electrolyser.

2.3.2 Hydrogen Storage

For the hydrogen refuelling station without on site production, storing hydrogen is usually done at the low temperature at the fuelling station. The hydrogen supply will be done by the truck periodically and the hydrogen will then be stored in the steel cylinders that operating around 200 to 300 bar. The hydrogen storage tank for the station without on site production is usually larger than the station with on-site production. This is because the continuous production of the hydrogen on site can cover up a part of the demand. However, the station with on site production still not able to be self sufficient because the hydrogen production on site is usually lower than the car fuelling demand. (Rothuizen and Elmegaard, 2013)

The hydrogen storage configuration is very relevance to the hydrogen fuelling system/ protocol. For the single tank storage system, the fuelling system will be booster fill to the vehicles, while for the cascade storage tank, it is possible to provide the cascade filling to the vehicles. The effects of different designs on the storage system of the hydrogen refuelling station by exploited the thermodynamics first and second law had been discussed in (Farzaneh-Gord et al., 2012), the author discussed the advantages of cascade system over the buffer system. Based on the results of the study, the main challenge of a cascade system could be the long fuelling time compare to buffer system but the author also suggested that this can be overcome to a more promising solution by appropriate sizing of the piping equipment.

	1 Tank	**3 Tanks**	**Savings**
Total mass [kg]	138.85	112.3	26.6
Power [kWh]	1.22	1.01	0.21
Time [s]	508	485	23
Total Cooling [kWh]	1.93	1.70	0.23
Peak cooling [kW]	61.7	65.1	-3.1

Table 2.5: Energy and Time Consumption Comparison for Single and Cascade Storage Tank Configuration(Rothuizen and Elmegaard, 2013)

2.4 Solar Energy

The solar energy activities in a larger scale had been very active in the recent years in Norway. In 2017, the solar market had captured the growth of 59% compared to 2016. The solar energy is harvested through a solar panel to generate electricity.

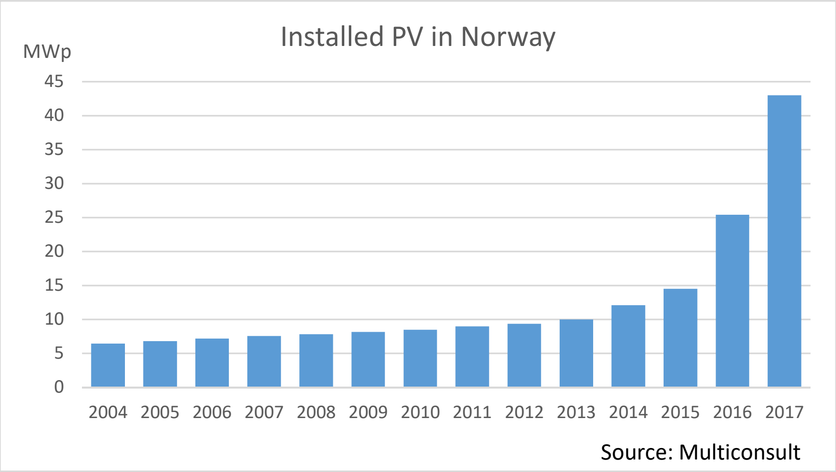


Figure 2.4: Installed PV in Norway as of 2017

2.4.1 Alkaline Electrolyser

Electrolyser is use to produce hydrogen from the electrolysis process, together with the Oxygen as the by-product. There are several technologies available for electrolyser, such as the alkaline electrolyser and the Polymer Electrolyte Membrane (PEM) electrolyser. The alkaline electrolyser has a better efficiency compare to the PEM electrolyser, which is 47%-82% that available at the industrial level. (Ursua et al., 2012) Based on the Nel Hydrogen products technical specification given on its own company website, the alkaline electrolyser operates at atmospheric pressure and 80 °C. The electrolyser operation is dependent on the sunlight availability. Besides, it is controlled by the buffer tank volume, that could overwrite to turn off the electrolyser production when the buffer storage tank is full.

From the field operational studies, it found that no failures had been recorded from the extensive operational trials of the alkaline electrolysis provided the handling of operation is correct. It also discussed that if the electrode corrosion issue that lead to the formation of electrolyte sludge could be resolved, the downtime need for periodic wash cycle could be reduced. Hence, the maintenance cost could save up to 50%, which calculated based on a new electrolysis plant with a 20years life expectancy. The alkaline electrolysis could provide a more reliable and more cost effective solution for the hydrogen production from the intermittent source of renewable energy.. (R.Gazey et al., 2006)

2.5 Supermarket Refrigeration System

A supermarket cold energy demands are usually supply by the refrigeration plant. The refrigeration plant keeping the desired cooling and freezing temperature to keep the goods in the best and safe conditions for the consumers by removing the excess heat from the storage room.

In the cold climate country, as in Norway, the refrigeration demand for the store air conditioning purpose is usually very small. The significant requirement for refrigeration is usually contributed by the food chilling and freezing purposes.

The CO_2 booster system with parallel compression is usually use for the centralized refrigeration applications. This CO_2 booster system is working in the trans-critical CO_2 system. The intermediate pressure receiver is used to separate the liquid from the gas. The liquid stream from the receiver is expanded and heated up in the evaporator. The low temperature (LT) evaporators operates from -30 °C to -35 °C, usually around 11 bar, while the medium temperature (MT) evaporators usually operates at around -5 °C and 28 bar. The flowrate of both evaporators are controlled by the pneumatic valve that control by the superheat temperature at the evaporators outlets. The superheat temperature is usually control within 5- 8 °C

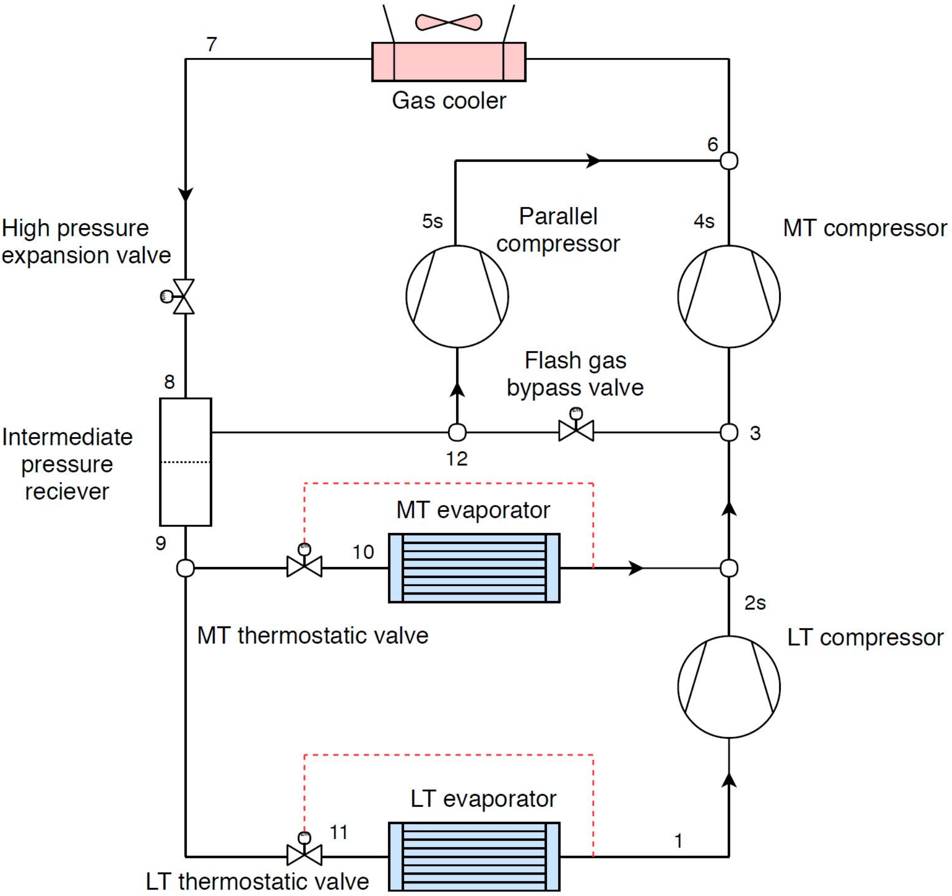


Figure 2.5: Schematic of Parallel Compression CO_2 Booster System(Birkeland, 2018)

At the intermediate pressure receiver, the expanded gas is recycled back for re-compression. The operating temperature at the receiver is critical to decide the performance of the refrigeration system. The higher temperature of the receiver, the more gas will be flashed off. This means there is less liquid refrigerants amount that would be utilized for the evaporators. The ambient temperature is related to the gas cooler outlet temperature, the higher ambient temperature, less heat can be rejected through the gas cooler, and hence leads to the higher expansion and pressure receiver temperature.

2.6 Norway as the Basis of Statistics Study

2.6.1 Energy System

The availability of abundant natural energy resources in Norway has made the country at a unique position to be a large energy producer. The energy balance statistics of Norway (Statistics Norway, 2017c) shows that the country overall energy production is ten times more than it consumes, which also means more than it's 90% energy production were exported to the market outside the country.

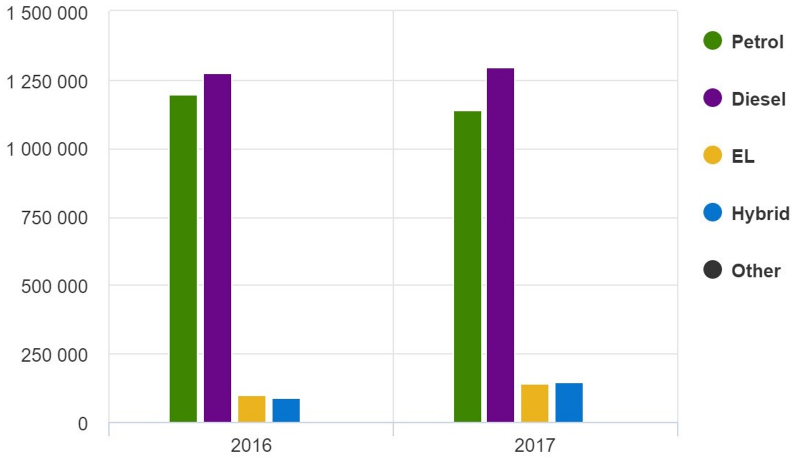
Hydro power has been the predominant energy source for electricity generation in Norway. Referring to the Norway reported electricity energy balance in August 2017, 95% of the electricity production are generated from hydro power. Out of the remaining small fraction of electricity produced, wind power had captured an increase of it's shares from 1.6% reported in the 2017, to the 2.3 % reported in 2018, both out of the total electricity production at the respective year. (Statistics Norway, 2017a)

Due to the abundant natural energy resources availability as discussed in the previous section and the geographically narrow and long shape country with the sparsely low population density, the deployment of Hydrogen in to the energy system in Norway has not be done very actively.

2.6.2 Vehicle Register

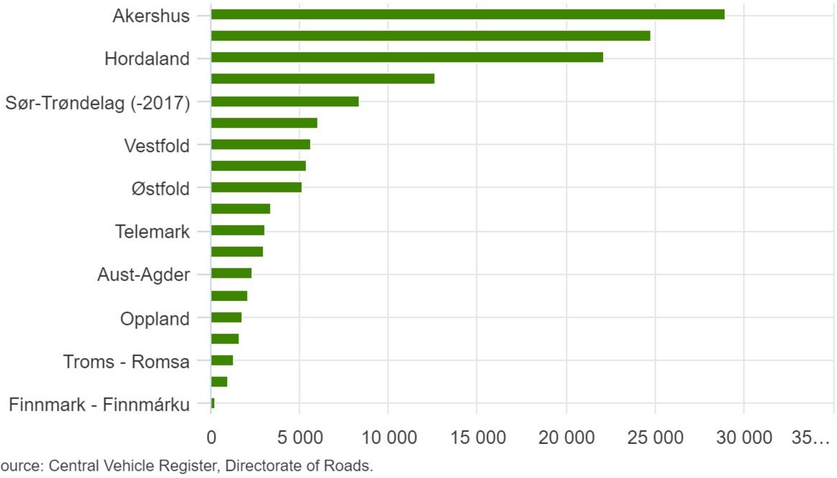
The hydrogen-fueled vehicle number that recorded was still insignificant. This could most probably because of the lack of hydrogen infrastructure development in the country. Comparing the climate friendly vehicles, the registered electric cars in Norway recorded over 40% increase in 2018 compared to the previous year. From the **Figure.2.6**, it can be seen that on the opportunity of phasing out the petrol and diesel vehicles, electrical cars and hybrid cars are doing a better job to grab the market shares. The HFCV, which is under the other category from the **Figure.2.6**, the figure is far away from any fuel type vehicles.

The low hydrogen activities doesn't means that the hydrogen technologies is in-profitable or not feasible. In order to travel long distance with zero emission on the road, the hydrogen vehicle is undoubtedly a better option, due to its energy compacted fuel. However, because of the interconnected relations of the hydrogen infrastructure availability and hydrogen vehicle owner convenience, a better planning will ensure the smooth transition from the current fuel to the hydrogen fuel vehicles is required. Although the hydrogen market is still new in Norway, the bright side is it's getting more attentions, everyone is having equal opportunity to be the key player in this new energy market.



Source: Central Vehicle Register, Directorate of Roads.

Figure 2.6: Registered Vehicles by Fuel Type in Norway.



Source: Central Vehicle Register, Directorate of Roads.

Figure 2.7: Electrical Car Register by each Country in 2017

Referred to the figure 2.7, the electrical cars that registered in the Sør-Trøndelag country is 8375 cars. This number will be use in the later section to determined the design basis of the project.

2.6.3 Road Traffic Volumes

By looking into the Norway road traffic volumes, which the emission statistics is directly relative to, the impact of emission reduction would be so small if the fuel cell vehicle replacement only implement on public transport like bus. This can be seen from (Statistics Norway, 2017d) that the buses share is only 1.3% and the amount is reduced by 3.3% over year 2012 to 2017. On the other hand, the passenger cars taken up 78.1% of the market shares and it in on the increasing trend. This means that in order to give a significant investment value of the hydrogen vehicle roll-out, the target must includes the passenger cars.

2.6.4 Greenhouse Gaseous Emission

Despite of the country relatively low CO_2 emissions compare to the world emissions, Norway anyway committed to reduce 30% of it's GHG emission by 2020, in consistent with the 2 °C world climate change by the United Nation (UN) panel on the Paris Agreement. At the climate change mitigation checkpoint of year 2020, the country however has recorded a 2.3% increase in emissions relative to 1990 baseline but a 1.7% reduction in the overall emissions in 2017 compared to the year before. Although Norway has look for alternative of negotiating a joint commitment agreement with European Union (EU) to entail joint commitment to meet the target (Royal Ministry of Finance, 2017), reduction emission undertakings need to be addressed and it can be solved by breakdown the different sources of country overall emissions.

Out of the 52.4 million tonnes total GHG emission (Statistics Norway, 2017b) in Norway (2017), 82.6% of them was contributed by the CO_2. The breakdown of emission sources had been visualized in figure 2.8. It shows that the largest emission of GHG was contributed by oil and gas extraction, manufacturing industries and mining, road traffic, in the descending order. The road transport taking up 17%

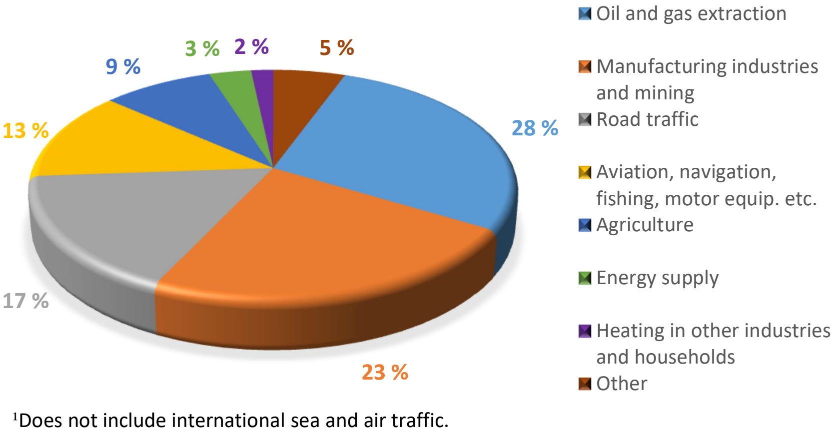


Figure 2.8: Emission of Greenhouse Gaseous by Different Source Categories in Norway, 2017. (Statistics Norway, 2017b)

Chapter 3

Energy Hub Framework and Definition

The integration of solar energy and hydrogen refuelling station in the project scope contributed the high intermittent level to the energy hub. There are too many possible open-ended designs that can be considered for an energy hub that will lead to never ending discussion. Hence, a proper project framework helped to give a guideline for the project development. The project framework was discussed in this chapter for an overview before the arguments for some particular system design could be done on the following chapter. Hence, the elements that included in the energy hub were discussed in general and the design requirements were defined in the following section.

The hydrogen infrastructure is the key component to move the hydrogen vehicles market. Hence, the hydrogen refuelling station is the driver of this study regardless of its high intermittent level. The hydrogen refuelling station contributed uncertainties to the project due to the highly intermittent consumption with an unpredictable pattern, while the solar power is due the the weather conditions. In order to reduce the uncertainties of the energy hub design, assumptions on the demands were made, several scenario and strategies were defined and recorded. The project is developed later on based on this energy hub base case design.

3.1 Energy Hub

The energy hub is the concept of a center to manage, standardize and control the multiple energy inputs and outputs to ensure the optimum energy flow. This energy hub concept/ approach was utilized to study and control on the energy flow of this project. **Figure.3.1** gave a clear overview of the energy hub interfaces to other system and also the flow of different energy types that available.

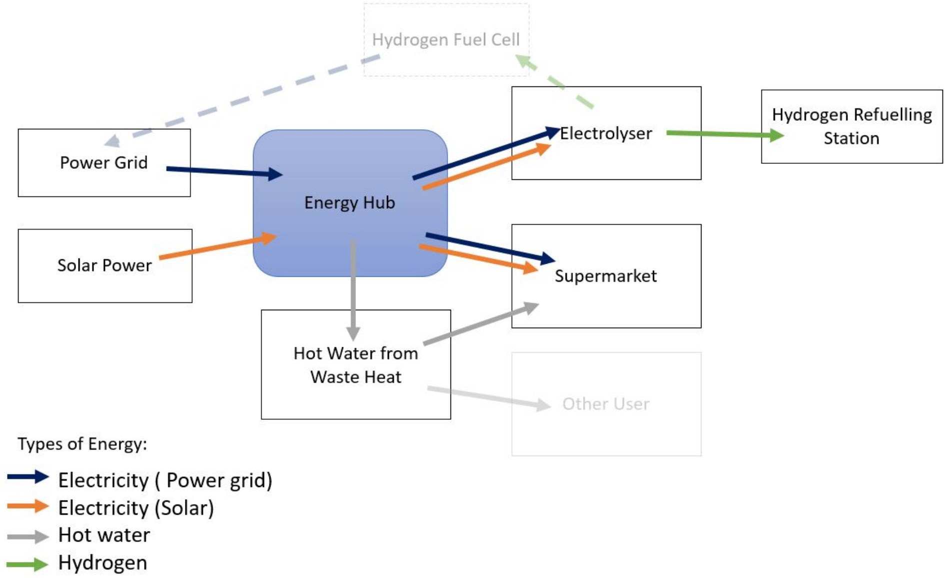


Figure 3.1: Energy Hub Overall Energy Flow Diagram and Interfaces

This stand alone energy hub are designed to generate electricity from the free available solar power and reduce the import of primary energy to the energy hub. The electricity generated from the solar panel could be use directly; or the excess production, will be use to generate hydrogen in the alkaline electrolysis system. The hydrogen generated will be stored in the high pressure storage system, and discharge to the vehicles during the refuelling process. There is a possibilities of low hydrogen refuelling demands and hence cause the excessive hydrogen in storage. The excessive hydrogen from the storage has the potential for export purpose or to re-generate electricity and connect to a local grid. However, the utilization of the generated hydrogen remains open and not discussed in this report.

An optimum control system of the energy flows is desired, either within the energy hub or across the interfaces i.e hydrogen refuelling station dispenser. The algorithms of the control system of the energy hub from a built facility are readily available and had passed the function test based on the literature review in the previous chapter. Hence, the control system algorithm is not part of the interests in this study.

3.2 Hydrogen Refuelling Station

The hydrogen is pre-cooled to a favorable temperature in order to start the vehicle refuelling process. The temperature limits various from the different types of refuelling stations. The refuelling station included in this study is design to handle the vehicles with a nominal working pressure of 350 bar and 700 bar at the temperature of -40 °C. In this case, it is the A70 refuelling station that had been described. The benchmark of a passenger vehicle refuelling rate is 1-7kg in 3minutes according to the SAE protocol.

One of the main component for hydrogen refuelling station is the dispenser. There are no specific operating conditions requirement for the dispenser itself. However, the number of refuelling station and the number of dispenser that available in the energy hub is decided. The refuelling station is designed to able to handle vehicles at both 350 bar and 700 bar pressure rating. At least 2 dispensers for each pressure rating is desired, and it means the energy hub will equipped with two 350 bar hydrogen fuel dispensers and two 700 bar hydrogen fuel dispensers.

3.2.1 Hydrogen Storage Tank

The on site production and compressor will usually not design to accommodate the peak demand. Hence, during the off peak hour, the compressed and cooled to ambient temperature hydrogen will be sent to the storage tank. The high pressure storage tank functions as the reservoir for the car refuelling during the peak demand hour. The cascade design storage tank will be different in tank pressure, typically between 400 to 600 bar for the low pressure tank, 600 to 800 bar for medium pressure tank and 900 to 1000 bar for the high pressure tank. The fuelling proceeds by levelling the pressure between the station and vehicle's hydrogen storage tank. The pressure levelling start from the low pressure tank until the average pressure ramp rate (APRR) cannot be achieved, it will then switch to the next pressure storage tank.

When the storage tank running low in volume or pressure,it will then again activate the electrolyser to produced hydrogen and the produced hydrogen can be send to the car refuelling when there is a demand or the flow can be diverted to the station storage tank.

The Hydrogen refuelling station consists of a compressor that could bring the hydrogen stream up to 1000bar for storage, or directly to the car refuelling when the station hydrogen storage tank running low on pressure. The compressed hydrogen will be cooled down to ambient temperature by cooling water before sending to vehicles or station storage tank. The compressor discharge the hydrogen at the very high temperature, which is approximately $160\,°\mathrm{C}$, and the waste heat can also be recovered and use for the hot water system and district heating.

The hydrogen will be cooled down to $-40\,°\mathrm{C}$ with the cooler after the pressure reduction valve to ensure the fast dispensing rate before charging hydrogen to the vehicles car. The APRR will be maintained at the outlet of the dispenser unit, the pressure reduction valve is controlled by measuring the pressure of the vehicles storage tank. The cooler is located downstream of the pressure reduction valve is because due to the inverse Joule-Thomson effect, the hydrogen will get heated up when it is throttled.

3.2.2 Hydrogen Demand for Refuelling Purpose

Up to date, the hydrogen demands recorded for vehicles refuelling is insignificant. However, by setting up the hydrogen refuelling station, more convenient will be brought to the HFCV owner. Hopefully this will encourage more selling and use of the HFCV.

Instead of plucking a number from the air to design the hydrogen volume required for refuelling purpose, the statistic for registered electrical car in Norway was taking as a reference, which is approximately 8000 cars up to the latest survey. The base case is made as that the HFCV will need 5 years time to catch up the market shares as compared to electrical car, and the roll-out of the HFCV will be at approximately 1600 cars per year. It is assumed that several Hydrogen refuelling station will be available within these 5 years but the worst case scenario was studied based on a single refuelling stations availability and the findings will be discussed further on the following chapter.

A full tank of hydrogen allows HFCV to travel up to approximately 550 km. Assuming the daily commute distance for a HFCV is 25 km and the distance is double during the weekend, this means a HFCV is travelling 225 km in a week. Hence, it can be said that for the case of short distance daily commuting purpose, a HFCV will need to recharge once in two weeks. The car refuelling is then randomly distributed in a any hours in the week.

Based on the assumptions made, the traffic for hydrogen refuelling station and each dispenser is calculated and tabulated below. At the first year, when 1600 HFCV had sold to the market, every car will need to be recharged once in two weeks. This mean with one hydrogen refuelling station available, the number of HFCVs that visited to the refuelling station will be 114 cars in a day. The hydrogen refuelling station is equipped with 2 dispenser for car, this means each dispenser is expecting 2 refuelling in an hour, to the total of 57 cars in a day. The list go on and up to year 5, with the same assumptions that made, one hydrogen refuelling station is still able to handle all the HFCV refuelling, provided that there is no congestion in traffic. However, this just simulate the worst case that could happen. More hydrogen infrastructure will need to be developed at the same time to increase the consumer convenience.

Year	HFCV on Road	HFCV Refuelling/day	Dispenser Traffic/day	Dispenser Traffic/hr
1	1600	114	57	2
2	3200	229	114	5
3	4800	343	171	7
4	6400	457	229	10
5	8000	571	286	12

Table 3.1: HFCV Roll-out Scenario within 5 Years and HRS Traffic

3.3 Supermarket Refrigeration System

Refrigeration system that utilized the natural fluid as refrigerant is favorable nowadays. In this project, the CO_2-Booster system will be the base case for the supermarket refrigeration system. The original CO_2 refrigeration cycle for supermarket application has two evaporators with 4 different pressure levels. In the low temperature cabinet, the refrigerant evaporates at -30 C and 11 bar. There will be 2 low pressure compressors that set-up in parallel, the refrigerant is compressed to the evaporation pressure before combined to the discharge stream of medium temperature cabinet. The refrigerant is mixed and further compressed to the condensing pressure. The compressed to high pressure refrigerant will be throttled through the high pressure reduction valve, to get the gas separated from the liquid in a receiver. The liquid collected will be further throttled to the LT evaporation pressures. The CO_2-Booster system described will be operating in the trans-critical conditions.

3.4 On-site Power Generation by Renewable Energy

There are several alternative of renewable energy sources that are able to generate free energy, i.e wind and solar. Both could fit into this energy hub integration concept. However, consider the case as described to integrated the energy flow with a supermarket, installation of the solar panel at the rooftop of existing store will give advantages to reduce the installation footprint. In addition, this option gives more favors to a larger building size, such as a cold storage warehouse, due to the larger rooftop areas that available .

The electrolyser will be producing pure Hydrogen and Oxygen as the by product from the water decomposition with alkaline hydrolysis at atmospheric pressure and 80 °C. The production stream of hydrogen will then send through a heat exchanger to cool down to the ambient temperature before sending to buffer tank. The buffer tank functions to ensure the steady flow input to the compressor before the hydrogen is compressed and cooled to storage. The buffer tank design conditions is dependent on the electrolysis production and it is not very critical to the overall design.

The hydrogen refuelling demand is fluctuating and highly intermittent. When there is no refuelling occurred, the hydrogen produced will be stored in the storage tank until the mass and pressure is exceeding the storage allowable conditions. It is possible that the electrolyser will need to stop production even there is a good sunny day due to the insufficient storage capacity. As shown in the **Figure.3.1**, it is possible to have the continuous hydrogen generation, provided that the produced hydrogen will send to re-generate electricity and sell to the grid, or building nearby. However, the provision to sell the excess produced hydrogen will not be discussed in this project. This topic is remained open until a more robust demands from the surrounding buildings or grid is confirmed.

3.5 Heating, Cooling Demands and Waste Heat Identification

The steady state energy flows simulation of the energy hub is established in HySys software. The details of assumptions of process flow will discussed in the following chapter. The following section collected all the data to give the project a proper frame for any further optimization.

3.5.1 Cooling Demands

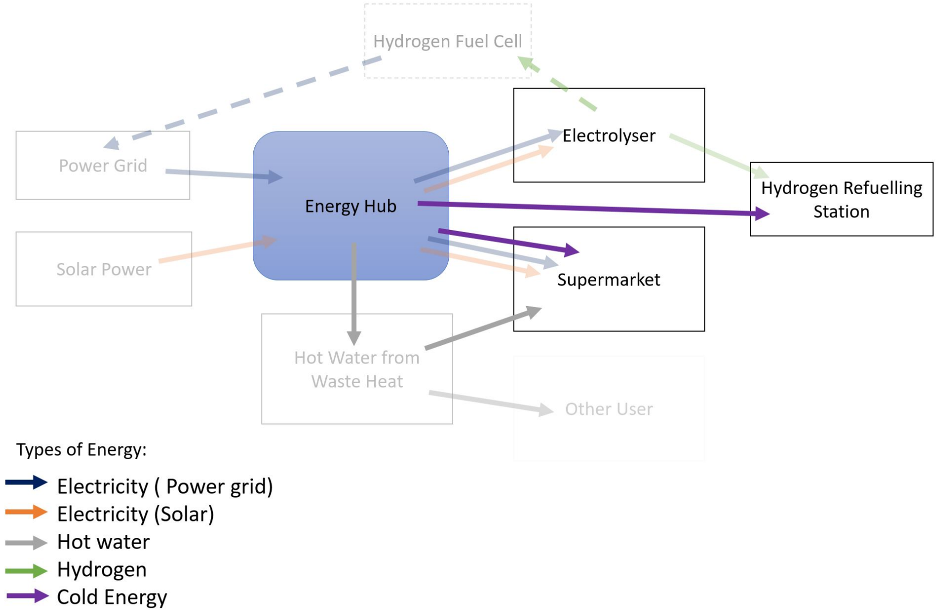


Figure 3.2: Simplified Diagram of the Cold Energy Flow in the Energy Hub

A supermarket cold energy demands are usually supply by the heat pump system. The cold produced by the heat pump system keeping the desired cooling and freezing temperature to keep the goods in the best and safe conditions for the consumers by removing the excess heat from the storage room. A supermarket has always installed with a heat pump system. The temperature level requirements of the refrigeration plant from the supermarket users and hydrogen refuelling station users had been identified. The two principal temperature levels in the supermarket with CO_2 heat pump system were the medium temperature (MT) and the low temperature (LT). MT is used for preservation foods and goods in the cold room, chilled display cabinets, etc while the LT provide keep the frozen food freezing. All the users requirement that had been captured are tabulated as below and was used to study for process design and integration study.

For the hydrogen refuelling station side, the refuelling temperature required is at -40 °C according to the SAE protocol. The cooling process of the refuelling station is intermittent and only required when the refuelling process is happening. The energy requirement given is based on the amount for one dispenser. Based on the discussion on the previous section, the energy hub will be equipped with 4 dispensers in total, 2 for 350 bar and 2 for 700 bar applications.

According to the idea of energy hub that having a central refrigeration system to provide the cooling demands to all the facilities.

	Desired Temp. [°C]	**Evaporation Temp.** [°C]	**Requirement [kW]**
Supermarket Chiller	below 14 and above 0	-10 to -5	65
Supermarket Freezer	lower than -12	-35 to -30	18
Supermarket Air Conditioning	ca. 20	ca. 3	10
Refuelling Station per charging*	- 40	below -50	60

Table 3.2: Cooling Demands in the Energy Hub

* intermittent user

Figure. 3.2 showed the relations of the cold energy users with the energy hub while **Table. 3.2** gave an overview of the cooling demands for all identified users the energy hub. In the next chapter, a study is carried out to find out the possibilities to utilize the existing supermarket heat pump system and supply cold energy to the hydrogen refuelling station, and at which pressure and temperature level is suitable for the integrated applications.

3.5.2 Heating Demands

For a supermarket building, the hot water demands is usually segregated in to 3 different circuits. The essential high temperature hot water system at 70 °C will be used as the domestic hot water system. A medium temperature level circuits at 33 °C will provided heat to the building for floor and space heating purpose. During the winter, when the weather conditions is below freezing level, ice and snow is most likely to piled up outside the store, a low temperature water system will be used for anti-freeze and snow melting purpose. For a commercial building, the demands for hot water system is usually not as much compare to the residential area. The demand for hot water system will be increased during the winter, where most of the energy will be used to keep the building heated.

A hydrogen refuelling station is usually un-manned. There are so far no other significant heating demands identified. Due to the large waste heat available in the energy hub, the hot water that can be produced is exceeding the demands within the energy hub. The provision to send the hot water generated to the grids is remained open

	Temperature [°C]
Floor Heating	33
Hot Water	70
Anti-freeze	0 - 15

Table 3.3: Heating Demands in the Energy Hub

3.5.3 Waste Heat Sources

During all these energy production and utilization processes, a lot of energy will be wasted, in the form of dissipated heat, mainly due to the low efficiency of the equipment. The compression process and electrolysis process produced large amount of waste heat. An old supermarket usually did not recovered its waste heat from the heat pump system, and reject at a distance from the room, typically at a higher point of a building.

For the energy hub approach, the large amount of heat generated will be recovered. These heats usually recovered through heat exchanger, that can be the good heat sources for other system especially the hot water system. The hot water system can be later used for other applications such as the floor heating or district heating water system. It is important to identify the waste heat source and the heat quality, i.e amount of heat available and the temperature level to find the best way for a heat recovery system can be design.

Reflecting by the simplest rules of heat conservation, the more waste heat that we could recovered, the less input energy that we will need to import to the energy hub. Hence, it is important to identify the waste heat sources and its temperature.

These heat sources includes:

Heat Source	**Temperature** [°C]	**Available Heat [kW]**
Electrolyser	80	73
CO_2 Compressor	120	350
H_2 Compressor	230	709

Table 3.4: Available Heat Sources in the Energy Hub

The heat rejection without recovery is not desired. The waste heat is recovered in the form of hot water. In the case that all the waste heat is recovered, the energy hub is producing more hot water than its demands. Based on current energy hub users, i.e supermarket and the un-manned hydrogen refuelling station, most of them has low demands on hot water system. The waste heat recovery system design to re-harvest the best quality of hot water system is carried out in the next chapter. However, the utilization way of produced hot water is remain open and will not be discussed in details in this project. One of the solution that identified so far would be connected to the district heating water (DHW) grid.

3.6 Energy Hub System Design Overview

The energy hub was design to handles 5 types of energy supply and demands within the energy hub. The interconnections between the energy flow had been address in the previous section. A schematic had prepared based on the framework described and attached in the Appendix A.1.

Chapter 4

System Design Case Study

This chapter break down the system design and several alternative designs for the particular system or equipment was evaluated. The related designs available were discussed thoroughly before the it is decided to selected as the base case design.

4.1 Evaporator Pressure for HRS cooling - CO_2 side

According to the SAE J2601 fuelling protocol, there are several designs of the refuelling station with different pressure rating and categories available. Taking the most stringent temperature requirement for the T40 station as an example, in order to achieve the vehicles fuelling duration without compromising any safety issue, hydrogen gas required to cool down to approximately -40 °C before it can start the discharging. A low temperature heat exchanger with a designated refrigeration system will be able to do that. The cooling is happened by transferring the heat to the refrigerant stream inside the heat exchanger, namely the low low temperature (LLT) evaporator. Several refrigeration technology, including a CO_2 system are available in the market in order to cool down the hydrogen to -40 °C.

For supermarket side, synthetic refrigerants for heat pump application are slowly phased out due to its harmful effects to the environment. It is a trends to utilize the natural fluids as the refrigerants in the heat pump system, and it is usually CO_2 system in this case.

It is not economical to keep separate heat pump system for hydrogen refuelling station and supermarket that requires duplicate capitals, operating and maintenance cost. A suitable heat pump system that able to accommodate both user needs is desired after the integration of energy system. Based on the cooling requirement that had been identified from the previous chapter, the studies over several possibilities of evaporators pressure level is discussed on the following.

As the hydrogen refuelling station refrigeration will be combined with the supermarket refrigeration system, and considering the supermarket system will be the main user that require constant low temperature supply, the log p-H diagram originally with the supermarket refrigeration cycle was use to study the feasibility to combine both systems. The log p-H diagram were prepared and the refrigeration cycle were plot in it to illustrate the supermarket refrigeration processes. Most of the key points in the refrigeration system of the supermarket were plotted on it. The process and the cycle were assumed to be ideal with no isentropic losses. Figure **4.1** were extracted from the DaVE, a post simulation processing software that would be discussed roughly in the later chapter.

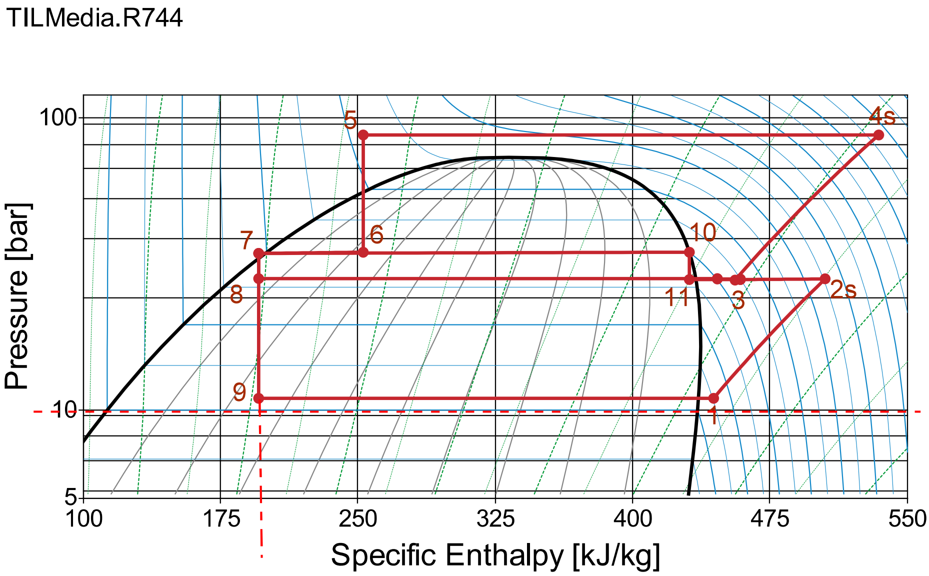


Figure 4.1: Log p-H Diagram of the Supermarket Refrigeration System

Based on the **figure 4.1** , the supermarket CO_2 system was expanded at a constant specific enthalpy of approximately 200kJ/kg to prior to enter the medium temperature (MT) cabinet and low temperature (LT) cabinet. After the combination of hydrogen refuelling station and supermarket refrigeration system, CO_2 temperature after the expansion is required to bring further down to lower than - 40 °C and exchange heat with the H_2 fuel. Originally for the supermarket standalone refrigeration system, the cooled CO_2 stream was expanded to point 8 (approx. -8 °C for MT purpose) and 9 (approx. -37 °C for LT purpose) before split to absorb heat from the evaporators. The requirement of -40 °C is quite close to the original LT cabinet requirement. Besides, there will be no heat ejection from point 9 to achieve the lower temperature of CO_2, the only way that could possible to do that is to further expand the pressure at constant or higher specific enthalpy from point 9 to a lower pressure and temperature. Based on the state chart reading, at the specific enthalpy of 199kJ/kg, the point at 9.5 bar will give the temperature of -41.5 °C (the intersection of the dotted line of constant specific enthalpy and pressure lines). At the new pressure level after the expansion, a higher vapour fraction will be obtained. Since only the liquid will be send for throttling and fed to the evaporators, the volume of vapour that is sent through the flash gas by-pass valve and re-compression will be increased. Hence, the power consumption at the MP compressor will be increased. A T-s diagram was also plotted based on the state point gathered from the supermarket refrigeration system. One of the observations from the T-s diagram below is of course the refrigeration power is increasing, which is due to the higher pressure ratio that increased the compressor work. It also can be seen that the expansion losses are also increasing. After the combination of both refrigeration system, the design at medium and high temperature side seems to be not affected, except on the extra compressor load due to the increased flow rate and consumption for the hydrogen refuelling station.

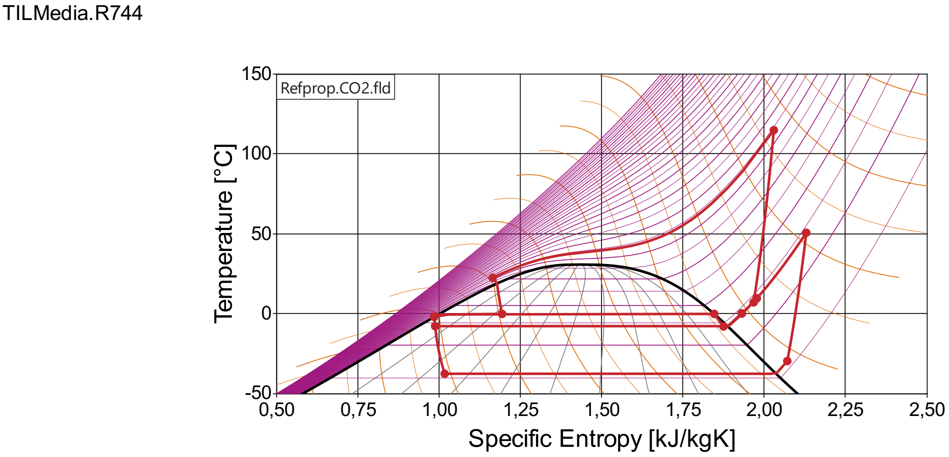


Figure 4.2: T-s Diagram of the Supermarket Refrigeration System

The expansion of the CO_2 at 199 kJ/kg to 9 bar resulted to the temperature of -$41.5\,°C$. This stream is required to reject the heat from hydrogen stream prior to the refuelling process. The desired temperature in order for the refuelling process to take place is -$40\,°C$. This means the approach temperature that allowed to design the heat exchanger is only $1.5\,°C$. This approach temperature might end up with an expensive heat exchanger, or a huge dimensional heat exchanger. None of this are desirable. The expansion pressure to 5 bar were also studied. The energy requirement for both pressure level in accordance to the system routing alternatives will be disccused in the following section.

4.2 Energy Hub Heat Pump System Design Optimization

The evaporation pressure level for the low low temperature (LLT) application had been addressed in the previous section. The integration of the supermarket heat pump system and hydrogen refuelling station refrigeration system remains complicated. A slight changes in the system design would give a big different in the capital and operating cost difference. The different system routing had been studied to find out the alternatives for the hydrogen refuelling station and refrigeration system integration. Other part of the refrigeration will remain unaffected after the integration. Hence, this optimization is only focus on the low temperature (LT) and LLT Three alternatives for the refrigeration routing had been figure out.

The first option will have its independent evaporators and compressor sets, that operates at the pressure level of 5-9 bar, few bar lower than the LT applications. A new stream withdraw the refrigerant from the refrigeration system is expanded to 5-9 bar and evaporates in the LLT evaporators, before send back to re-compression to the MT pressure. Evaporation of CO_2 at the pressure range of 5-9bar corresponded to the temperature of -$42\,^{\circ}\mathrm{C}$ and -$56.5\,^{\circ}\mathrm{C}$. The re-compression pressure is 28 bar.

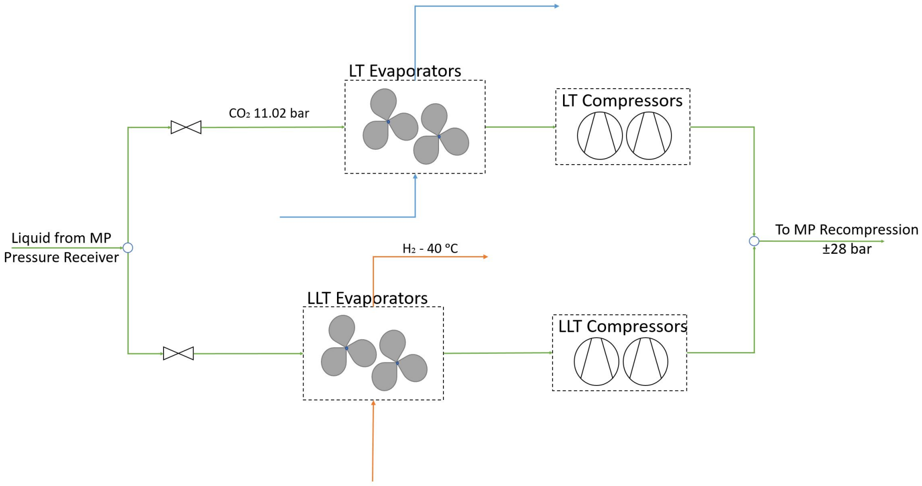


Figure 4.3: Energy Hub Integrated Heat Pump System Design Option 1

Option 2 shows that the hydrogen cooling will be sharing the same pressure level and compressors set with the existing LT applications. The pressure level is set at 5-9 bar to accommodate the hydrogen refuelling temperature requirement. A single stream that withdraw refrigerant liquid from the MP pressure receiver is expanded to 5-9 bar and split into both LT and LLT evaporators to exchange the heat. The heated gas that coming out from both evaporators will then combined again for re-compression to 28 bar.

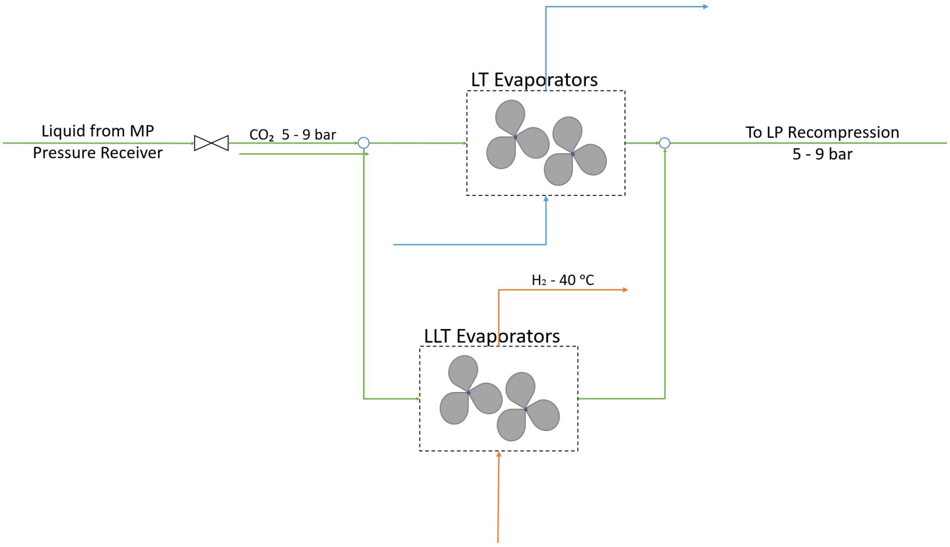


Figure 4.4: Energy Hub Integrated Heat Pump System Design Option 2

Option 3 will also be sharing the same pressure level and compressors set with the existing. However, the routing will be different from option 2. The liquid refrigerant will be expanded to 5-9 bar, first go through the LLT evaporator and get heated up to -37 °C, and then further heated up in the LT evaporator to the compressor suction temperature. The heated gas will then re-compressed to 28 bar through the LP compressors.

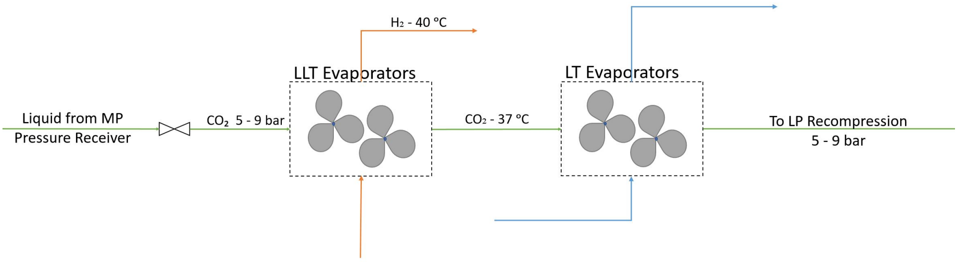


Figure 4.5: Energy Hub Integrated Heat Pump System Design Option 3

Before the simulation on the energy demand had been carried out, alternatives 2 and 3 gave a better advantages due to the less equipment counts for the system. Both alternatives save the cost of a set of expensive rotating compressor. However, after the simulation had been carried out, it seems that alternative one require a lower energy demands, which is 3 kw and 5kw lesser compared to alternative 2 and alternative 3.

4.3 Electrolyser Size and Hydrogen Refuelling Demand

Model	Unit Capacity [Nm^3/hr]	Prodcution [kg/day]	Power Consumption [kWh/Nm^3]	No. of Car filled	Power [kW]
A150	150	ca. 310	3.8 - 4.4	44	1.4
A485	485	ca. 1000	3.8 - 4.4	142	51.2
A3880	3880	ca.8200	3.8 - 4.4	1170	409.7

Table 4.1: Cooling Demands in the Energy Hub

Due to the intermittent usage of the low temperature from the hydrogen refuelling side, study had been done to visualize the power usage of different vehicles refuelling scenario. According to the adequate hydrogen refuelling station size that accommodating the ambitions of hydrogen vehicles roll-out case, a few random patterns of vehicles charging scenario were also defined to check the power requirement on the low temperature supplies.

From the existing H2 plant from Nel Hydrogen, several model had been picked to study on its production capacity and power consumption. The electrolyser technology that used in these design is the alkaline electrolyser. For those technical information that were given in a range, the number of the higher end was picked for the study. The results can later scale up and down to match the hydrogen refuelling station capacity requirement. Usually, a HFCV consumes 1-7kg per charging. 7kg were used for the calculation.

4.4 Refrigeration System Selection

The CO_2 refrigeration is favorable for the supermarket applications. However, after the integration with hydrogen refuelling station, the CO_2 refrigeration system might not be the case. From the **Figure. 3.2**, it can be seen that the intermittent refrigeration energy demands for the refuelling purpose is almost equal to the supermarket daily operation demands.

Besides, based on the dynamic simulation of the model, the expansion from the high pressure resulted in almost one third of the flash gas produced. The heating demand within the energy hub is little, hence the recovered waste heat has lost his strength to provide the hot water back to the energy hub.

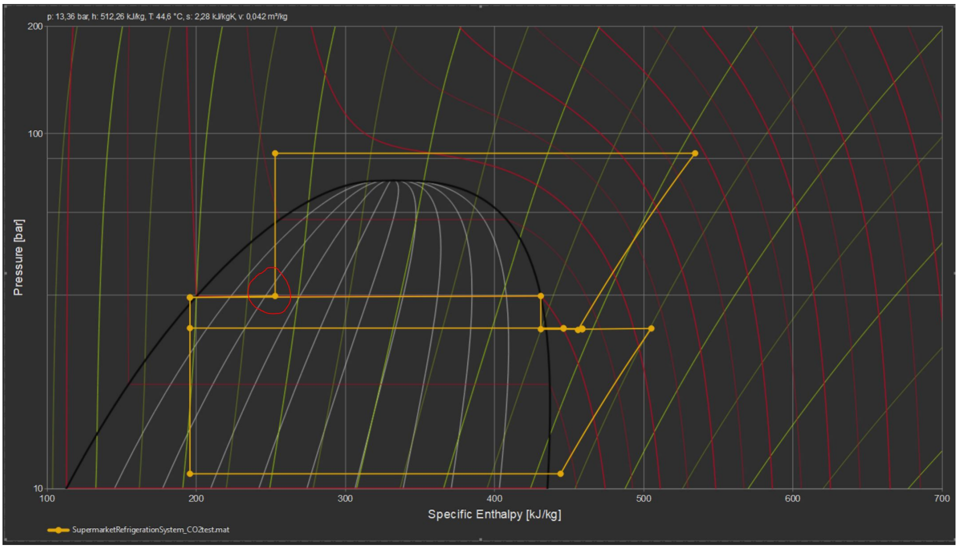


Figure 4.6: State Chart for the Energy Hub Refrigeration System

Chapter 5

System Modelling and Results Discussion

Several software had been use to study the the system design of the Energy hub with integrated hydrogen refuelling station.

5.1 Steady State Design Modelling

Before the dynamic simulation could be done, the simulation data had been collected from the steady state simulation in the HySys software. Model for each study case had been established and studied. Several assumptions had been made in general before the simulation can be carried out. The assumptions that had made are listed below:

- Pressure lost from the heat exchanger and the pipeline are assumed to be zero
- The adiabatic efficiency of a compressor is 75%
- The cooling medium are available at 20 °C

5.1.1 Hydrogen Compressor

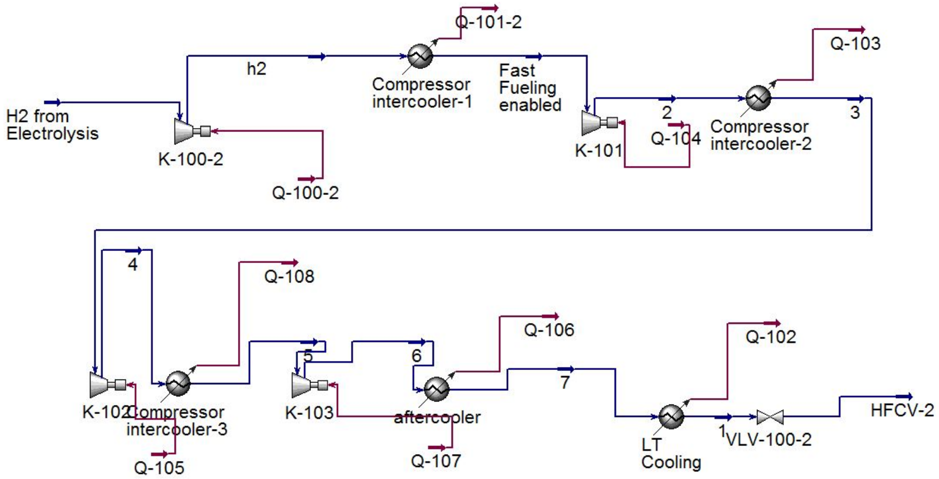


Figure 5.1: Steady State Simulation - Hydrogen Compressor

Figure. 5.1 showed the model of the hydrogen compression from the electrolysis to the hydrogen refuelling station dispenser. The compression is break down into several stages to achieve the reasonable pressure ratio and compressor outlet temperature. the results from the steady state simulation were tabulated. There are no data available for the hydrogen compressor, and the power requirement could be having a great deviations from the hydrogen compressor that available on the market.

Compr. Stage	**Compr. Outlet Pressure and Temp. [bar]; [°C]**	**Pressure Ratio**	**Power [kW]**
1	12; 235.2	4.00	172.9
2	50; 229.6	4.17	175.7
3	200; 224.0	4.00	174.7
4	875; 245.7	4.38	214.0
		Total	737.3

Table 5.1: Results from Steady State Simulation - Hydrogen Compressor

A sensitivity simulation were also carried out to study on the effect cooling medium temperature on the compressor work. The new cooling medium temperature that used for simulation is 7 °C. The results for each compression stages is recorded and compared to the cooling medium at 20 °C. The 1st stage power consumption is not affected by the cooling medium temperature. However, the results showed that the total power that could be saved for the overall power is 32kW.

Compr. Stage	**Power,**7 °C **[kW]**	**Power,**7 °C **[kW]**
1	172.9	172.9
2	175.7	165.2
3	174.7	164.4
4	214.0	202.8
Total	737.3	705.3

Table 5.2: Results from Steady State Simulation - Hydrogen Compressor

5.1.2 Available Waste Heat- Hydrogen Compressor

As mentioned in the assumptions, the available cooling medium temperature is assumed to be 20 °C. A 5 °C approach temperature is use for the heat exchanger to simulate the utilities duty.

Compr. Stage Cooling	**Compr. Outlet Pressure and Temp. [bar]; [°C]**	**Pressure Ratio**	**Duty [kW]**
1	12; 235.2	4.00	195.0
2	50; 229.6	4.17	165.4
3	200; 224.0	4.00	163.5
4	875; 245.7	4.38	185.1
		Total	709.0

Table 5.3: Results from Steady State Simulation - Hydrogen Compressor

5.2 Energy Hub Heat Pump System Design

Three system design alternatives to integrate the energy hub heat pump system had been discussed thoroughly in the previous chapter. The steady state simulation were set up to study on the compressor work required, in order to supply the same cooling energy demand to each of the evaporators. The set up were established based on the system routing alternatives that proposed in the previous chapter. The COP within these 2 evaporators and compressor has been calculated. Based on the plotted **Figure. 5.3**, the best solutions is the first alternative.

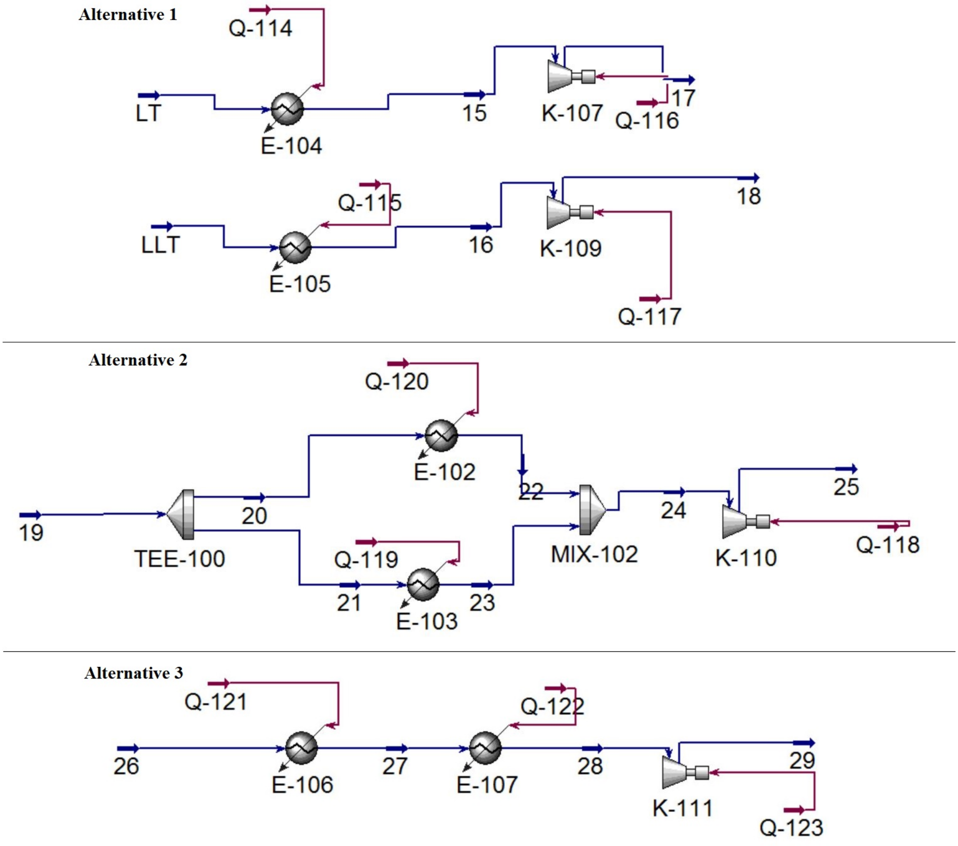


Figure 5.2: Steady State Simulation of Energy Hub Integrated Heat Pump System Design

The coefficient of performance for each alternatives was calculated

$$COP = \frac{\dot{Q}}{\dot{W}}$$

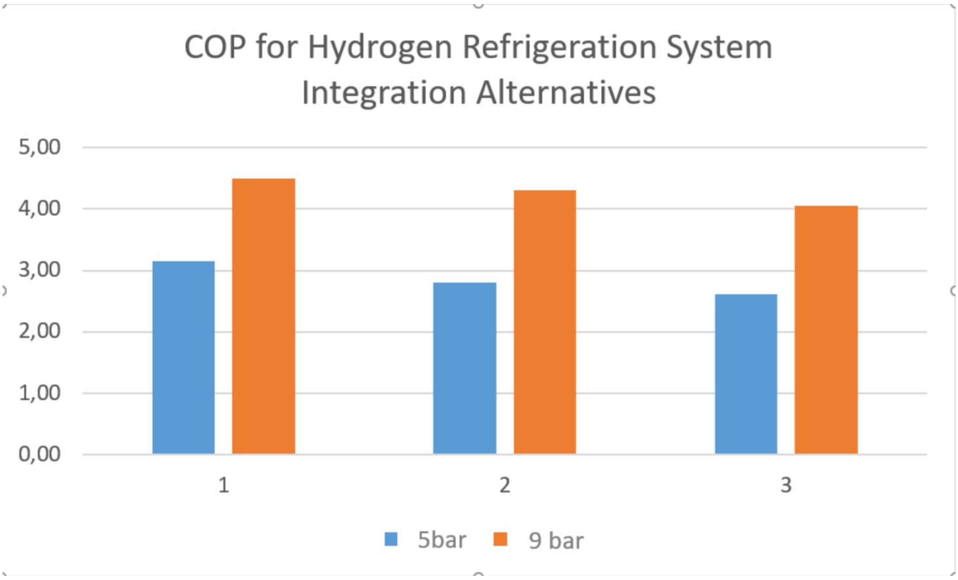


Figure 5.3: COP for Hydrogen Refrigeration System Integration Alternatives

5.3 Dynamic Simulation Modelling

Dymola is a software that using the open Modelica modelling language as basis, which the existing model libraries from many engineering fields are easily available to run the dynamic simulation for a more complex integrated systems. The engineering services and software company TLK-Thermo GmbH has built a library product namely the TILMedia Suite from Dymola software and open Modelica functions, that consists of a comprehensive of different fluids and its thermophysical properties, equipment and etc. The library also features with several pre-modelled key components for a thermal system, i.e. heat exchangers, pumps, compressors, valves and other.

The TILMedia Suite package process the information into 3 different substance categories at the very first point, in order to carry out the optimal calculation with different equations of state, interpolation methods for each categories. System Information Manager(SIM) is used to store and record the replaceable substance information for each categories in the model. The substance categories are segregated by different colour in the library and the available categories are ideal gas, real gas and the vapor liquid equilibrium fluid. The TILMedia Suite is also able to accessing external database like Refprop, and integrated with other applications like MATLAB, Phython, Excel and etc.

NTNU has access to the TILMedia Suite library and this project had utilized the library for the modelling development. Hence the energy hub system modelling had been built on these basis.

5.3.1 Model Set-up

The hydrogen gas was intended to modelled as a VLE fluid due to its potential to compress to a very high pressure and some verification steps had been carried out to verified this. The results that obtained from the model is compared with respect to the Hydrogen state chart data in the respect of specific enthalpy at certain pressure and temperature. A simple model that consisted of a stream with positive energy input were used for the validation and the changes in temperature and enthalpy were checked. The figure below shows the model setup for the verification purpose.

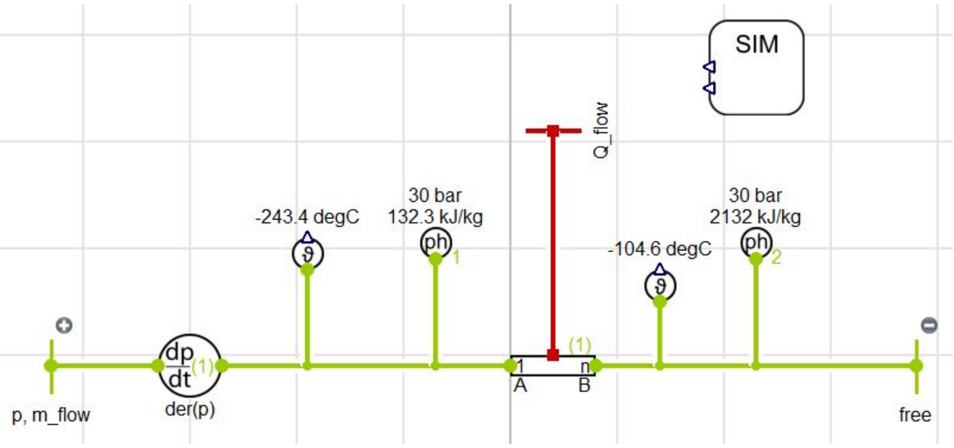


Figure 5.4: Model Setup for the Verification Steps

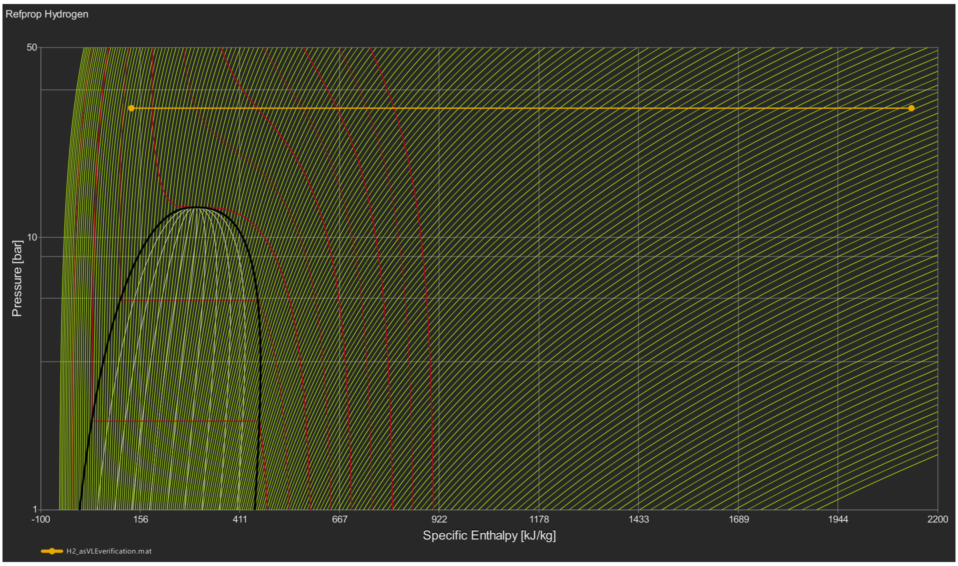


Figure 5.5: Results from the Verification Steps

5.3.2 Full System Dynamic Simulation Results and Discussion

The full system dynamic simulation model was attached in the **Appendix.A.2**. The dynamic simulation were run for 20000 s and the results had been extracted and studied.

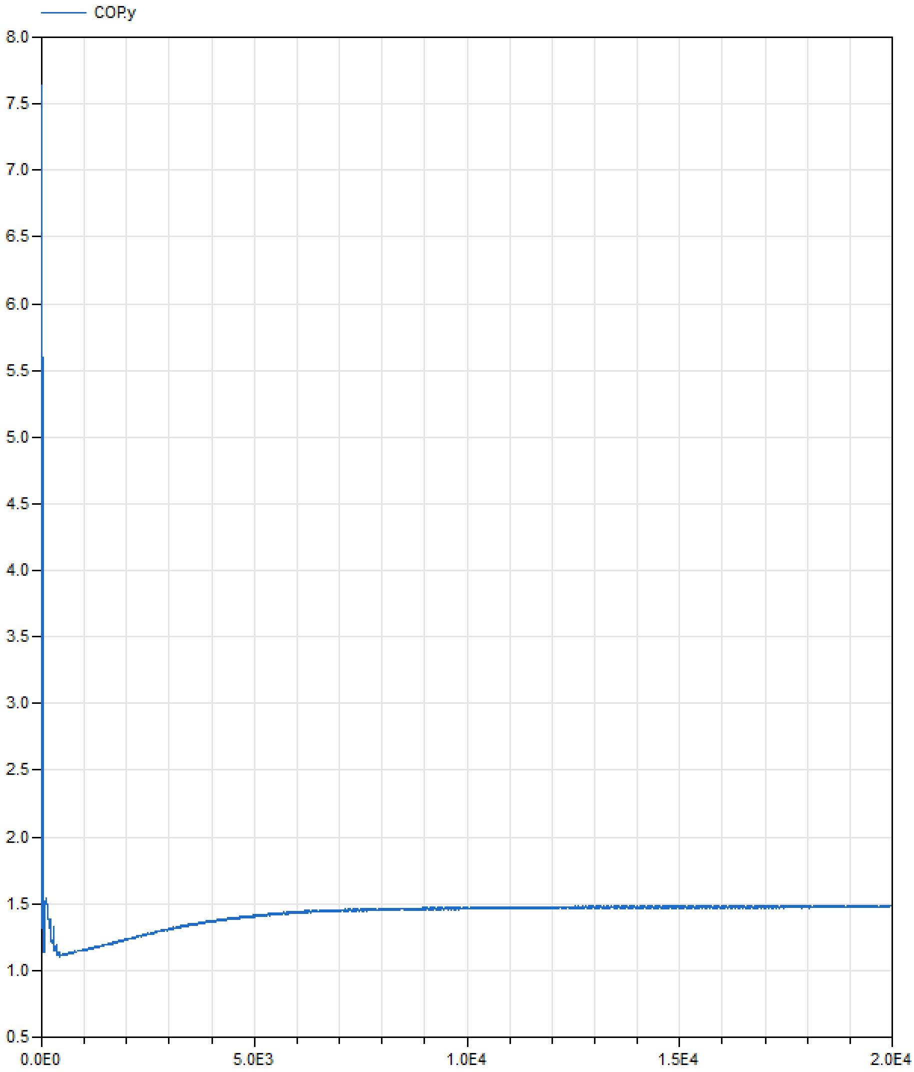


Figure 5.6: Processed COP from the Dynamic Simulation Results

The overall COP from the dynamic simulation had been processed in **Figure. 5.6**. The overall system give the COP of 1.5 after it reach the steady state at around 10000s. The low COP that recorded at the beginning are most likely due to the establishment of the heat exchanger temperature and pressure requirement. The same fluctuation pattern can also be observed in **Figure. 5.6**, the energy demand for MT cabinets.

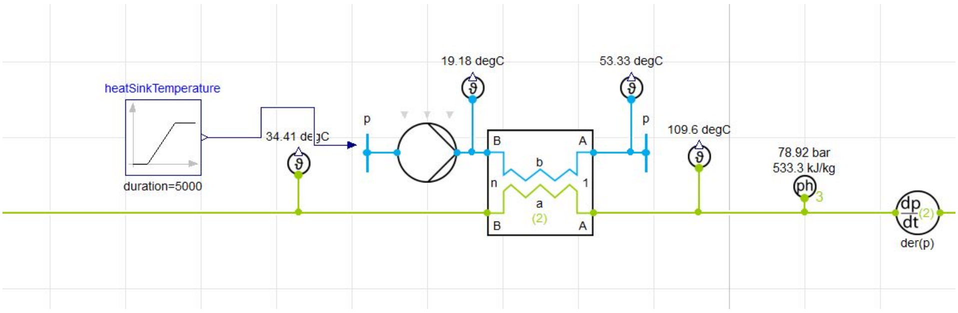


Figure 5.7: Dynamic Simulation for Increasing Evaporation Temperature

Another dynamic simulation had been carried out to study the relation between the CO_2 evaporation temperature and the power after the integration of hydrogen refuelling station. **Figure. 5.7** showed the set up of the temperature ramp that introduced at the 5000s and **Figure. 5.9** showed the results from the simulation. The MT cabinets power demands is stabilizing before 5000s and started to increase, in accordance to the increasing evaporation temperature.

Appendix. 5.8 showed the energy demand for each evaporators. The blue colour line indicated the energy demand for hydrogen cooling; the red colour line indicated the energy demand for LT cabinets; while the green colour lines indicates the energy demand for MT cabinets.

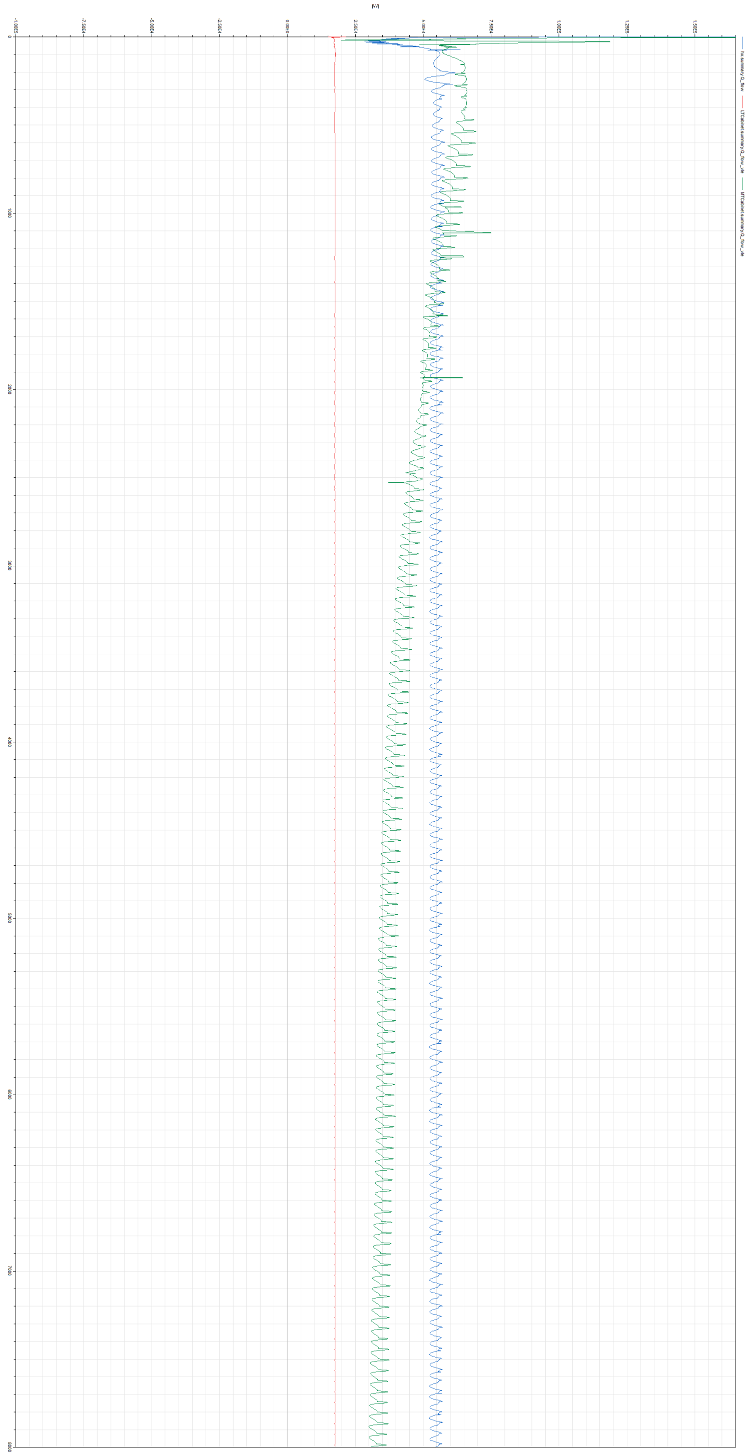


Figure 5.8: Energy Demand for each Evaporator from the Dynamic Simulation

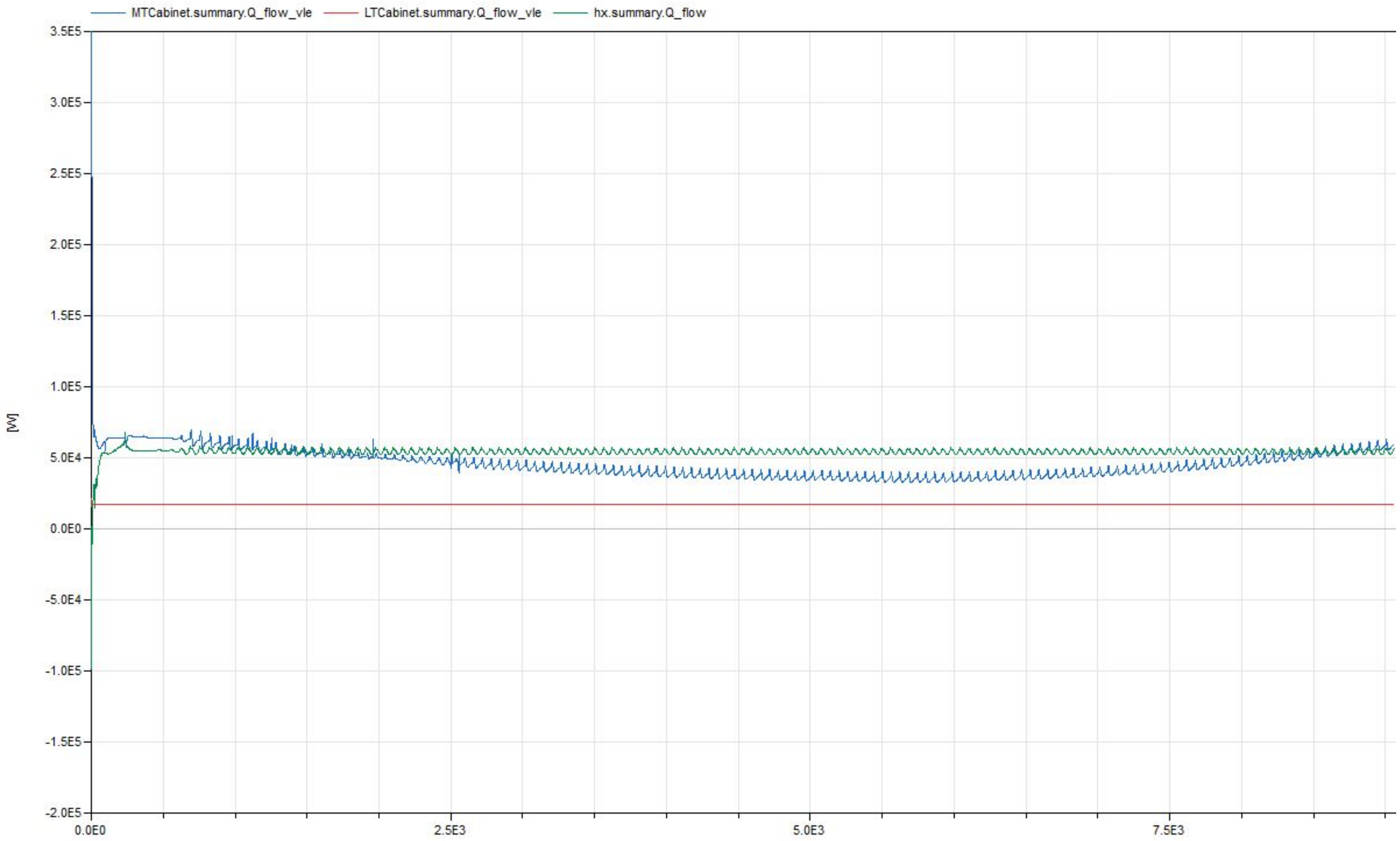


Figure 5.9: Energy Demand for each Evaporator from the Dynamic Simulation at Increasing Evaporation Temperature

5.4 Simulation Post Processing

DaVE, a software by TLK-Thermo GmbHto post-processing to display and visualize the dynamic simulation data sets. This software provided the interface to import the refprop data and results file from the Dymola. The existing built in function available made the state chart and refrigeration cycle generation become very handy with this software. Several refrigeration cycles that had been extracted from this software had been disccussed in previous section.

Chapter 6

Conclusion

A comprehensive literature review that study on the country existing hydrogen facilities and activities, market available technologies and feasibility had been carried out. A technical feasible concept for the energy hub with hydrogen refuelling station integration has been developed. This concept describes the framework of an energy hub with a clear boundary, with provision of a new scope to be included.

A system design had been established based on the concept. It gave an overview of the energy available and the distribution in the energy hub. Optimization from different case studies had further improved the system design. The base case of energy hub is integrated among solar energy plant, supermarket and hydrogen refuelling station. However, the energy demands varies a lot for different types of building, i.e the hydrogen refuelling station requires a lots of cooling, a supermarket need a lots of electricity and cooling, while the potential user for the recovered waste heat could be those building that has very high hot water demand. The energy so far producing a lot more hot water system than the demand. Hence, the potential amenities could be integrated into this energy hub would be a swimming pool centre or household area. The CO_2 refrigeration system that utilized in the energy hub is one of the contributors to the huge hot water production. Conventionally, a CO_2 refrigeration system bring advantages to a supermarket with the ability of producing hot water for the domestic uses, floor and space heating and space heating system. The balance demand between the cold and heat in a supermarket make CO_2 refrigeration system favourable. However, after the integration of energy hub, the large cold demands in hydrogen refuelling side had affected the balance between cold and waste heat produced. This resulted in the excessive hot water production.

Study from the dynamic simulation also showed that after the integration of the hydrogen refuelling syste, the MT cabinet took up to 5000s to stabilize the CO_2 refrigeration system. Due to the intermittent requiremnt of the hydrogen refuelling, CO_2 refrigeration system might not be the best option to bring down the temperature.

Chapter 7

Further work and Recommendations

Throughout the study of this project, several improvement that can be done that would bring benefits to the projects had been captured. This chapter captured the recommendations for the future works.

From the developed energy hub overall energy flow diagram, there are several high intermittent sources or consumers were included in the study. In order to carried out the study, a lot of assumptions had been made in this project, mainly from the hydrogen refuelling side, due to the lacks of field data. The loose boundary of the design scope contributed a lot of uncertainties to the project. The low market demand on new energy is the key that contributed to these uncertainties.

The solar power that designed in this project, is dedicated to the energy hub consumption. The fresh fund to install the new solar panel dedicated to the energy hub use might not bring in high economical value to the energy hub. While at the existing renewable farm, excess generation with insufficient consumption has always be a big problem when it come to the renewable energy farm planning, sizing and development, which the excess energy is often simply lost to nowhere. The renewable farm is usually big scale. Hence, the economical value of this project will be increased if the waste produced energy from the renewable energy farm would be utilized instead of installing a new solar panel.

With the integration of the energy management at the renewable energy farm, it makes the farm design can be captured to a higher degree of freedom since it is possible to run the renewable energy far all time at its optimum capacity, and turn the excess energy diverted to the electrolysis system to produced hydrogen, getting free energy that is usually wasted by stopping the production.

From the results of this project, after the integration of the hydrogen refrigeration with the energy hub refrigeration system, studies showed that to cool down the H_2 temperature to lower than -$40\,^{\circ}\mathrm{C}$ with the 9.5 bar $\mathrm{CO_2}$ gave a better technical results. However, the approach temperature of $1.5\,^{\circ}\mathrm{C}$ between $\mathrm{CO_2}$ and H_2 stream was too close, this give a very stringent requirement to the heat exchanger design in the later stage. Due to the inefficiency of the heat exchanger, a proper sizing and evaluation on the heat exchanger side is necessary.

The $\mathrm{CO_2}$ refrigeration system is bring economical value to a supermarket due to it ability to generate hot water for heating purposes and the balance demands between cold and heat in the premises. After the integration, the

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Appendix A

Appendix

A.1 Energy Hub Design Flow Diagram

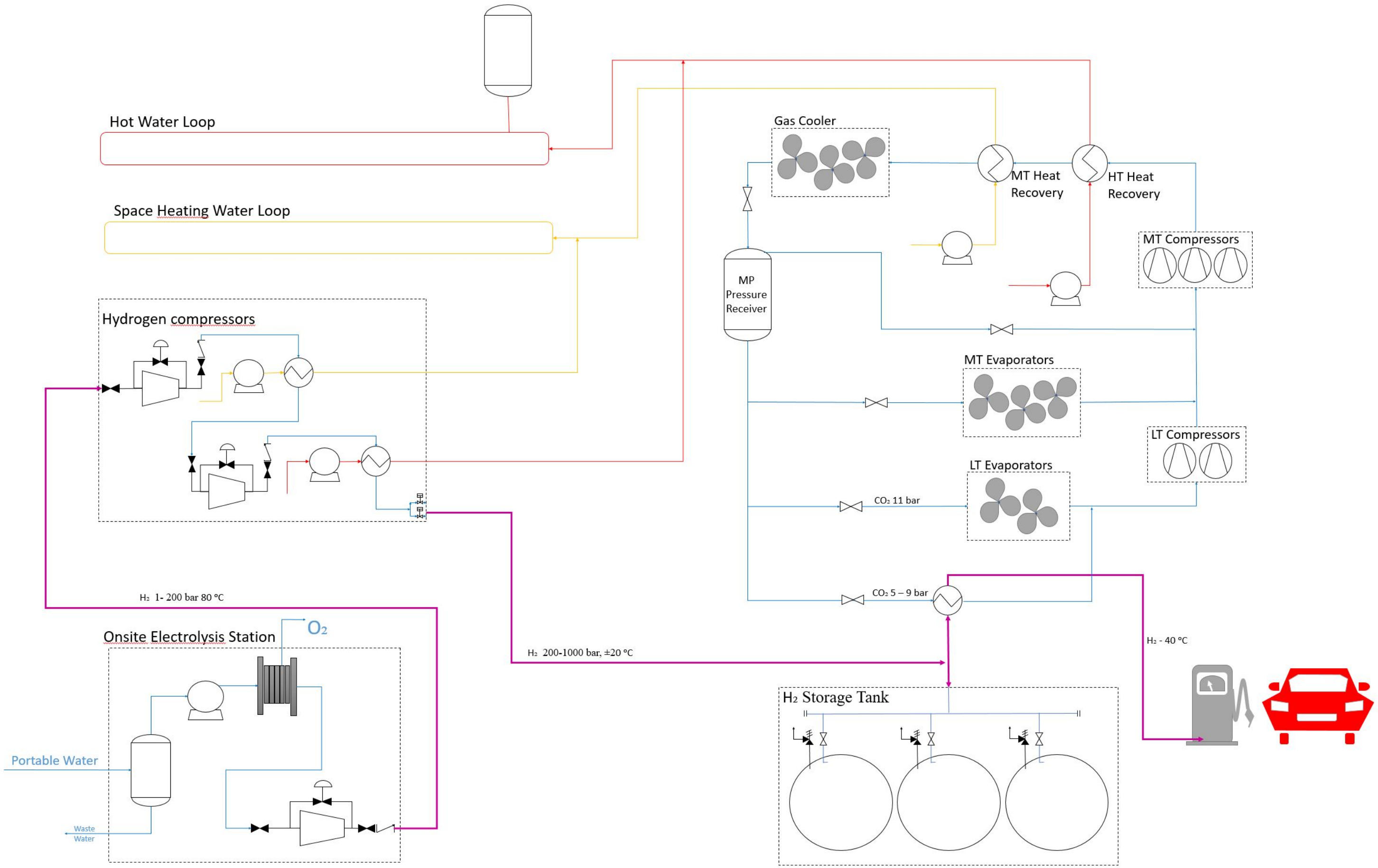

Figure A.1: System Design of the Energy Hub with HRS

A.2 Dynamic Simulation Set-up in Dymola

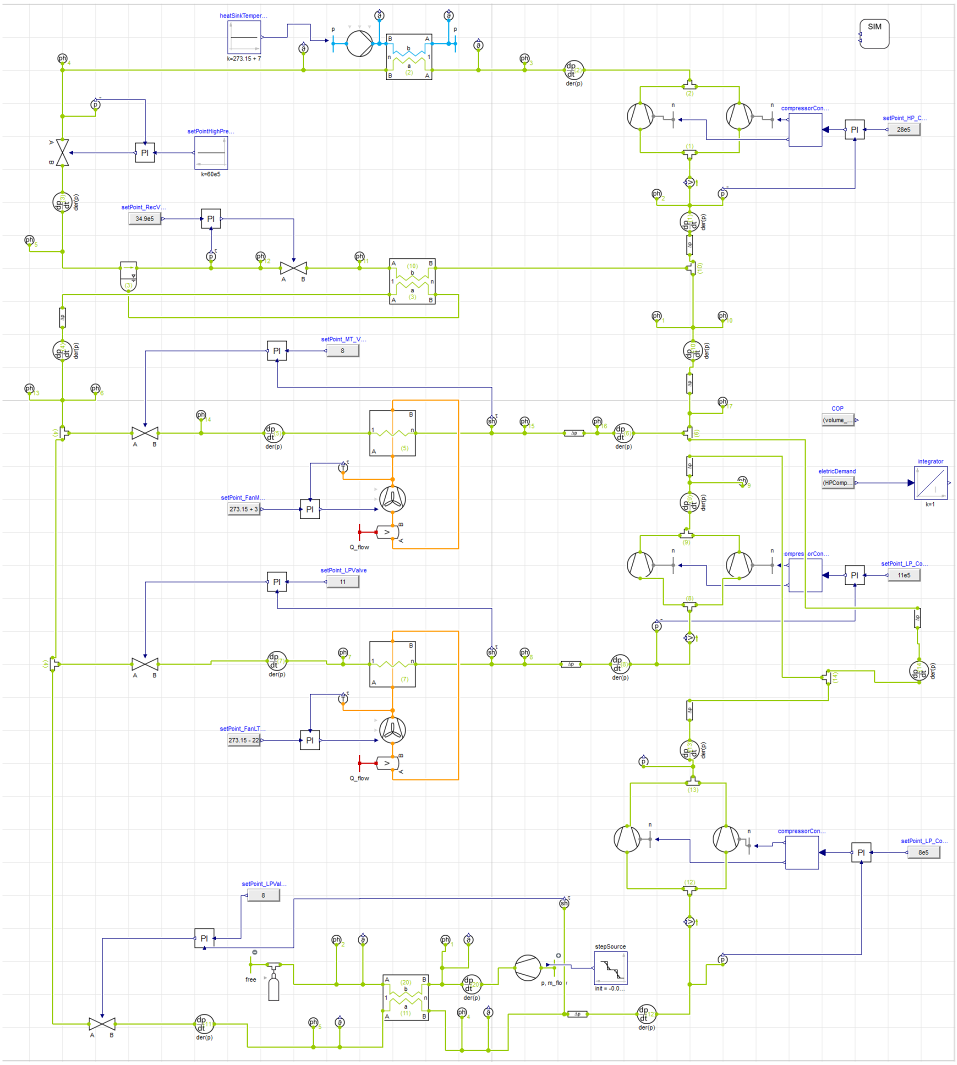

Figure A.2: Overall Simulation Set-up Diagram in Dymola

A.3 Key Results from the Dynamic Simulation

Figure A.3: Full Results for Q Flow of each Heat Exchanger