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Hydrogen Production at Hellisheidi Power Plant

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ABSTRACT

One of the premises for stable operation of a geothermal power plant is stability in steam utilization. Production wells are sensitive to operational changes and heat changes have the greatest impact in two phase systems. When market demand is low it may be necessary to vent the geothermal steam in order to maintain stability of the steam flow from the production wells, decreasing efficiency of valuable energy. This inflexibility in geothermal operations makes it very challenging for production to follow the load demand and it may result in temporarily reduced electricity prices. In this paper, the authors will seek to answer whether a solution can be found when demand decreases, and prices drop, for example during nights and weekends, by a demand-side mechanism in the form of a flexible power-intensive user. The use of an electrolyser during low load hours is investigated. Hydrogen production by electrolysis is very energy intensive, and the latest types of electrolysers can provide flexibility in ramp up and ramp down time while at the same time supplying the transport sector with a renewable energy source. The electrolyser is started when it is foreseeable that electricity demand is low, and then turned off when the demand rises again. This paper will discuss how to use variation in demand to create value and consider whether it is feasible to use an electrolyser for this purpose. At first stages the control of the electrolysis will be from the plants' operators, but in future the equipment could possibly serve as a grid balancing tool. The project is part of a European Union development project; Hydrogen Mobility Europe (H2ME).

1. INTRODUCTION

Orka náttúrunnar (e: ON Power) is taking part in a European Union supported project, Hydrogen Mobility Europe (H2ME), alongside Skeljungur, Íslensk Nýorka and Íslenska Vetnisfélagið.

The H2ME initiative is a European project that is supported by the European Union through the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU). The project aims to deploy hundreds of fuel cell hydrogen cars, vans, trucks and refueling infrastructure across 8 countries in Europe. The project is made of two phases, H2ME, which started in 2015, and H2ME–2, which will end in 2022. Over the course of this time, more than 1.400 vehicles and over 45 hydrogen refueling stations will be dispersed around the countries. It will create the first pan-European network, and the world's largest network of hydrogen refueling stations (Hydrogen Mobility Europe, 2018) .

Hellisheidi is the largest geothermal power plant in Iceland with 303 MWe electrical production capacity and currently 133 MWth thermal capacity serving the capital's district heating system. The closeness of the power plant to the capital area plays a role in why ON Power is interested in hydrogen production but first and foremost it is the possibility of utilising the geothermal energy more efficiently by producing hydrogen at low load hours.

2. BUSINESS IDEA

The business idea is based on the following principle: Hydrogen is produced at Hellisheidi, on-site at the geothermal station at times when it is suitable, i.e. low load hours. At Hellisheidi, the hydrogen gas is pressurized to 200 bar and put on vessels. The vessels are then transported in containers, around 200 kg of hydrogen in each container, to three refilling stations where hydrogen is available for end-customers. At the stations, hydrogen is pressurized from 200 bar to 800 bar for refill purposes. The refilling stations are all a part of the flex-fuel stations under the brand Orkan. The location of two of the stations are in Reykjavík; one in Miklabraut where there is dense traffic and another one in Vesturlandsvegur. The third refilling station is at Fitjar, which is close to Keflavík international airport. Figure 1 shows briefly the important locations in the project.

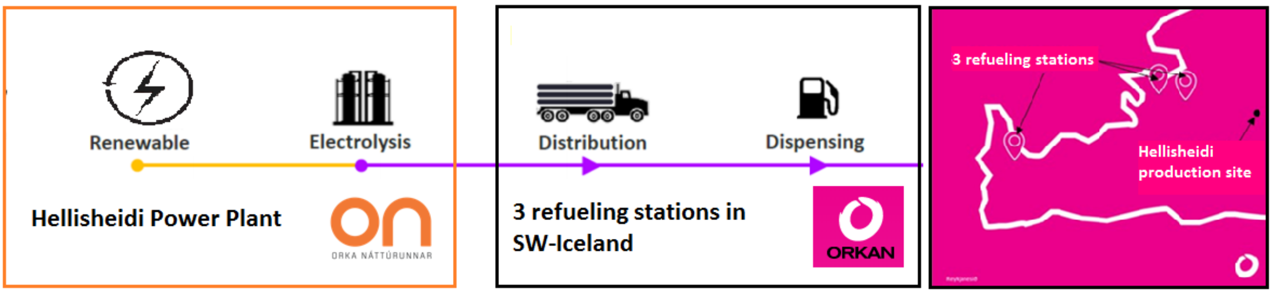

Figure 1: Boundaries of stakeholders' roles and the location of production site and refilling stations

3. MARKET OVERVIEW OF THE ICELANDIC TRANSPORTATION SECTOR

Iceland is in a unique worldwide position, as considerable parts of the nations' primary energy consumption is met with renewable energy sources. The largest remaining sources for CO_2 are in the transportation and industry sector, as Figure 2 below shows.

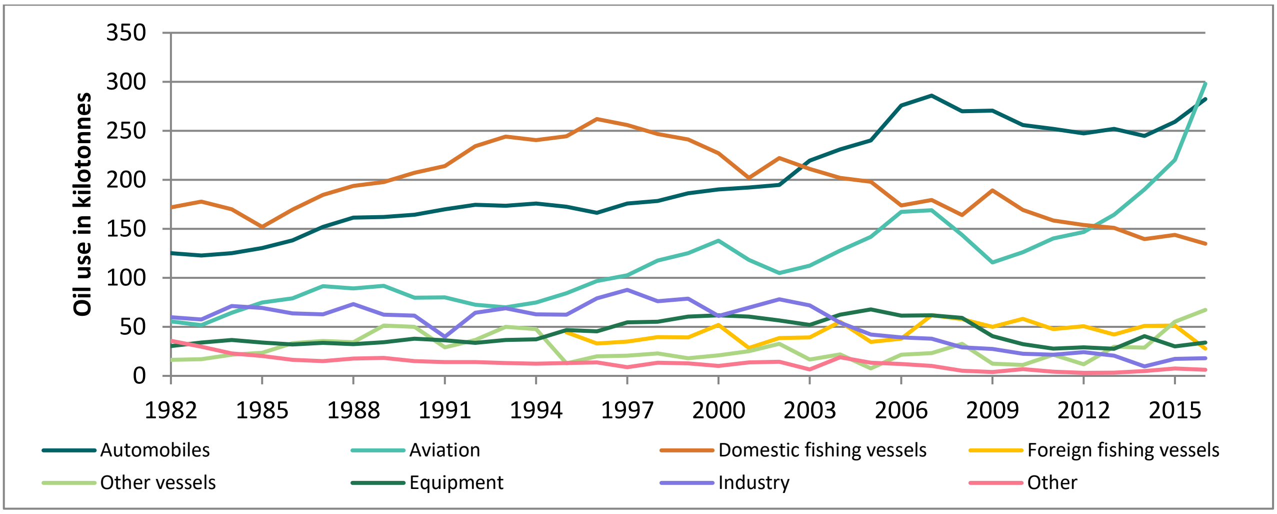

Figure 2: Oil use in Iceland by categories (Orkustofnun, 2017).

The automotive sector has been on top of the chart in recent years with respect to the amount of annual oil usage. However, the oil use in aviation has risen immensely over the last few years as a result of the tourism boom that started in Iceland in 2011.

Battery Electrical Vehicles (BEV) and Plug-in Hybrids (PHEV) have become the leading technologies to improve the share of renewable energy as a fuel source in the transportation sector. They are gaining increased popularity at the expense of Internal Combustion Engines (ICE). This transition is especially prominent in cars for personal use. For trucks and other heavy-duty vehicles, hydrogen remains a promising fuel and a few producers, such as Toyota and Hyundai, have announced new models for the market (Green Car Congress, 2019). The infrastructure for hydrogen filling still has a long way to go in order to make hydrogen vehicles a favourable option. However, Nikola Motor Company has announced that they will strengthen the hydrogen station network in USA to expand the use of hydrogen fuelled cars, also known as Fuel Cells Electric Vehicles (FCEVs), beyond California where most of them already are (Ohnsman, 2019). That could be a start of an increase in demand for both hydrogen production and FCEVs.

FCEVs are a favourable vehicle option when it comes to long, continuous use, and heavy-duty use that cannot be fully addressed by BEV or PHEV. However, complementary nature of these technologies is furthered by the fact that progress in BEV, PHEV, and FCEV development benefit each other due to their many shared components and development options. Figure 3 gives an overview of what type of fuel is suitable for different vehicle sizes.

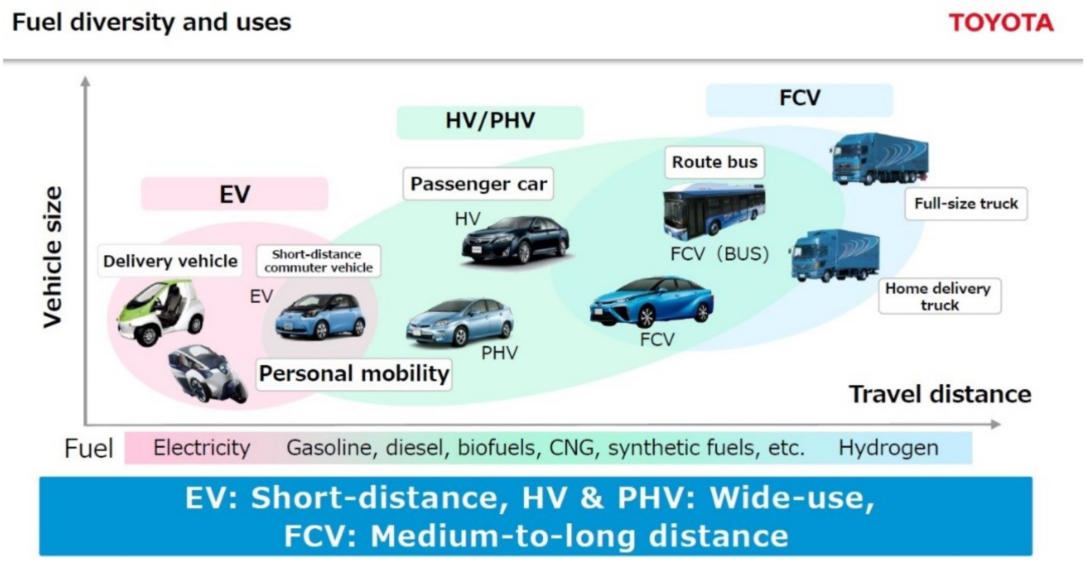

Figure 3: Suitable fuel options for different vehicle sizes (Kane, 2015).

Hydrogen is expected to be the lead fuel type for longer distances and heavy vehicles. The main reasons for that is the range of the FCEVs (+500km), the short amount of time it takes to fill a tank full of hydrogen as well as the significant weight advantage of the fuel cells over comparable battery electric trucks.

4. GREEN HYDROGEN

Hydrogen is one of the most common elements in the earth's crust, it is available as a natural resource in a bound form as water or hydrocarbons. Hydrogen is the simplest member of chemical elements. It is a colourless, odourless, tasteless gas. Its density is the lowest of any chemical element, 0,08999 grams per litre, which is the reason why it occurs to a very small extent in the earth´s atmosphere. By comparison, a litre of air weights 1,29 grams, 14 times as much as hydrogen. Hydrogen changes from a gas to a liquid at a temperature of -252,77°C and from liquid to a solid state at a temperature of -259,2°C. It is slightly soluble in water, alcohol and a few other common liquids. Even though hydrogen is very reared it can be produced in different ways such as by fossils fuels like natural gas, biomass, coal and oil as well as with renewable energy sources such as wind, solar, geothermal and hydropower. Hydrogen can even be captured from waste from industrial processes.

Hydrogen is used in several chemical industries. Around 55% of the world's hydrogen production is used for ammonia production where it plays a vital role in the manufacturing process, 25% in refineries and 10% in methanol production. Steam reforming is the most common way to produce hydrogen from fossil fuels. Another way to produce hydrogen is by using electrolysis where an electric current splits water into hydrogen and oxygen. Hydrogen by electrolysis is currently only a small part of the world's annual total hydrogen production but its share may increase due to increased inflexible renewable production in Europe.

The result of using an electrolyser where the electricity is produced by a renewable energy source is that the hydrogen will also be considered renewable. As 99, 99% of all electricity production in Iceland comes from renewable energy sources and there is enough of water around, the possibility of hydrogen production via electrolysis seems like a great option to improve the air quality in Iceland as well as to reduce the dependence on oil from foreign countries (Samorka, 2015).

Table 1 shows the CO_2 footprint of hydrogen production by comparing different technologies; steam reforming, using electrolyser where the electricity comes from fossil fuels (EU average emissions) and using electrolyser where the electricity is from Hellisheidi geothermal power plant (European Industrial Gases Association AISBL , 2018). The table shows the significant difference between those methods from emission point of view.

Table 1: CO_2 footprint of different hydrogen production methods

Technology	kg CO_2 emission per Nm^3 of H_2	Reaction*
Steam reforming	0,8	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$
Electrolysis, fossil fuels	2,6	$2H_2O \rightarrow 2H_2 + O_2$
Electrolysis Hellisheidi	0,0368**	$2H_2O \rightarrow 2H_2 + O_2$

* Simplified reactions

**The emission of CO_2 in NCG per kWh in 2018 multiplied with electrolyser efficiency (Orkuveita Reykjavíkur, 2019).

Table 1 shows that hydrogen production via an electrolyser using electricity from Hellisheidi has by far the lowest emission of CO_2 per Nm^3 of hydrogen. Electrolysis with fossil fuels emit around 7.000% more and steam reforming around 2.000% more CO_2 compared with when the energy comes from Hellisheidi.

5. WHY IS ON POWER INTERERSTED IN HYDROGEN?

ON Power has ambitions to be the national leader in the transition to sustainable transportation and has already contributed dozens of fast-charging electric stations on strategic positions throughout the country. Being a frontier is not limited to electricity. By producing hydrogen on-site, ON Power takes a fuel-type neutral position.

Another factor in ON Power's interest in hydrogen is the possibility of combining hydrogen production to the geothermal power production at Hellisheidi power plant at times when it is suitable. The role of geothermal power plants in the electrical system is mainly to produce base-load electricity, while hydropower deals with flexible loads. Currently, ON Power has limited access to hydropower, flexible loads are mainly met via purchases from other producers. By producing hydrogen during low load hours and turning off the hydrogen production during higher load hours, the utilisation of Hellisheidi's power production is improved.

On Power is determined to take good care of the environment. In that journey, ON Power, alongside its parent company OR, are performing experimental practises at Hellisheidi to capture CO_2 and other sour gases, like hydrogen sulphide, NCG's from the power generation at Hellisheidi. The gases are mixed with water and reinjected back into the ground. With time, the gases will turn into minerals that will be stored in the subsurface. These projects are called CarbFix and SulFix (CarbFix, 2014). Figure 4**Error! Reference source not found.Error! Reference source not found.** shows the portion of NGC gases from Hellisheidi power plant that have been reinjected. In 2018 the proportions were 33% of CO_2 and 74% H_2S.

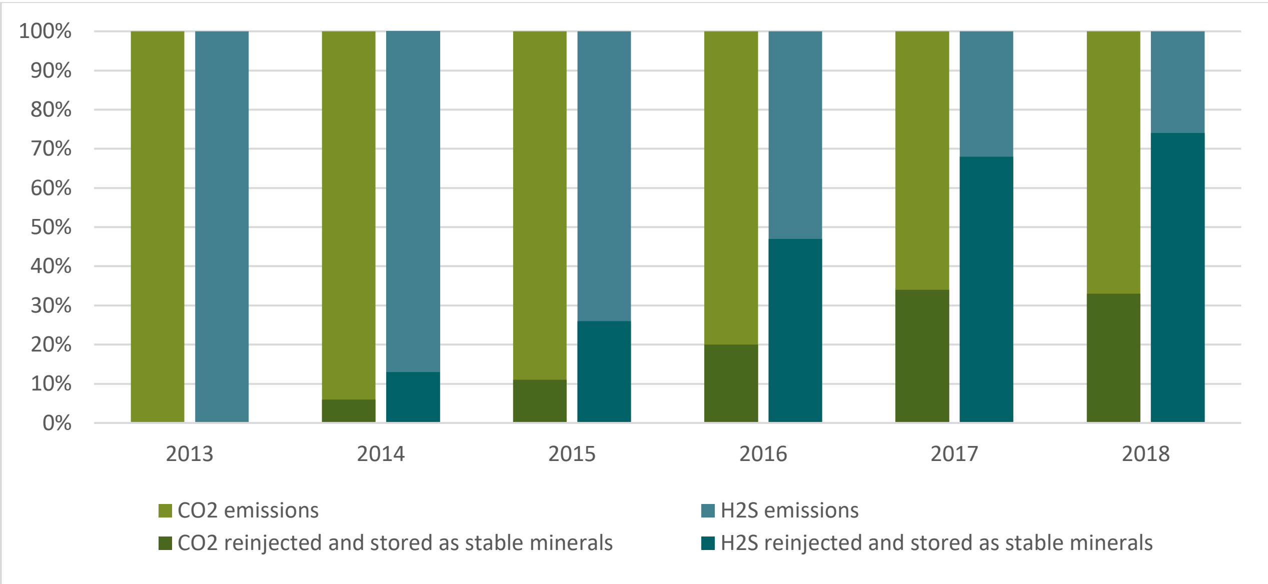

Figure 4: Annual percentages of reinjection of H2S and CO2 emissions from the Hellisheidi geothermal power plant in 2013-2018 (Orkuveita Reykjavíkur, 2019).

ON Power has also an ambition of utilising excess resource streams from the power generation by setting up an area near the power plant where businesses can work with one another in order to fully utilise the different streams and side products of their operation (Orka náttúrunnar, 2018). Hydrogen production seems to be a logical next step to utilise the power plant more efficiently while reducing the amount of CO_2 in the atmosphere.

6. HYDROGEN PRODUCTION AT HELLISHEIDI

ON Power made an agreement with Skeljungur and Íslensk Nýorka in May 2018 to be a part of the hydrogen development in Iceland. ON Power's role is to produce hydrogen via electrolysis by using electricity from Hellisheidi power station. The H2ME project subsidized the purchase of the electrolyser, which was in a way a driving force to start the process.

The electrolyser is supplied by Nel hydrogen and is of Alkaline type. It can be operated from 20% up to 100% of its design capacity, 30 – 150 Nm^3/h (2,7 – 13,5 kg/h). If the electrolyser is in operation for 8.000 hours per year it can produce 108.000 kg/year of hydrogen and the CO_2 emission is around 44.160 kg.

The container holding the electrolyser from Nel can be seen in Figure 5.

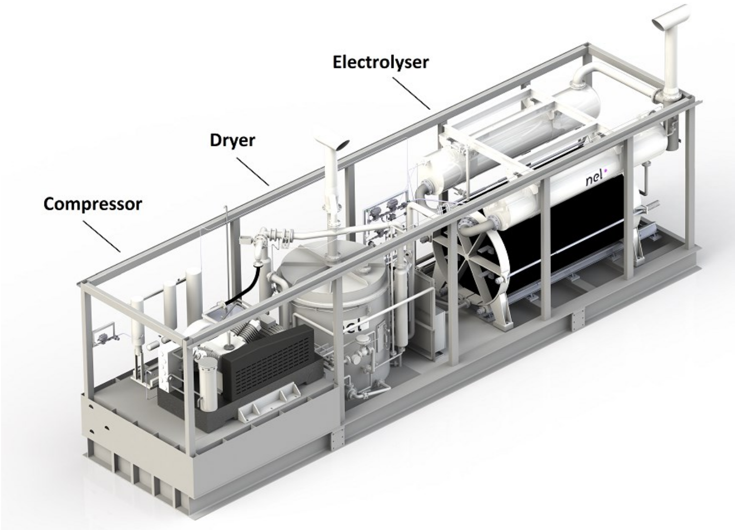

Figure 5: An overview of the electrolyser container (Nel Hydrogen, 2019).

In the electrolyser, a direct electric current is led through water. The product of this process is hydrogen and oxygen. After the electrolyser the hydrogen goes through a dryer unit that is used to purify the hydrogen gas before it goes through a compression unit and thereafter to a storage unit.

6.1. Plant Layout and Storage

As a result of fire and risk assessment, the hydrogen plant is located about 100 metres from the power plant on a 280 m^2 concrete floor. A fence is around the production to limit access as well as two CCTV cameras, so plant operators can monitor the station. On all gates are electrical access systems that are connected to the power plant´s access system. To open the gates, an access card is needed, and the system logs any card that is swiped, valid or invalid. Figure 6**Error! Reference source not found.** shows the hydrogen plant at Hellisheidi.

Figure 6: Hydrogen plant, Hellisheidi power plant is in the background

The container holding the electrolyser is the one on right side on the figure while the smaller container holds the control equipment's, rectifier and transformer.

Figure 7**Error! Reference source not found.** shows different views of the hydrogen plant. Notice that the concrete floor on the right figure, is the area where the hydrogen vessels will be situated and connected to the hydrogen plant via a pipe. The location of these vessels is better shown in Figure 9.

Figure 7: The hydrogen plant

Real and schematic pictures of trucks and containers is show in Figure 8.

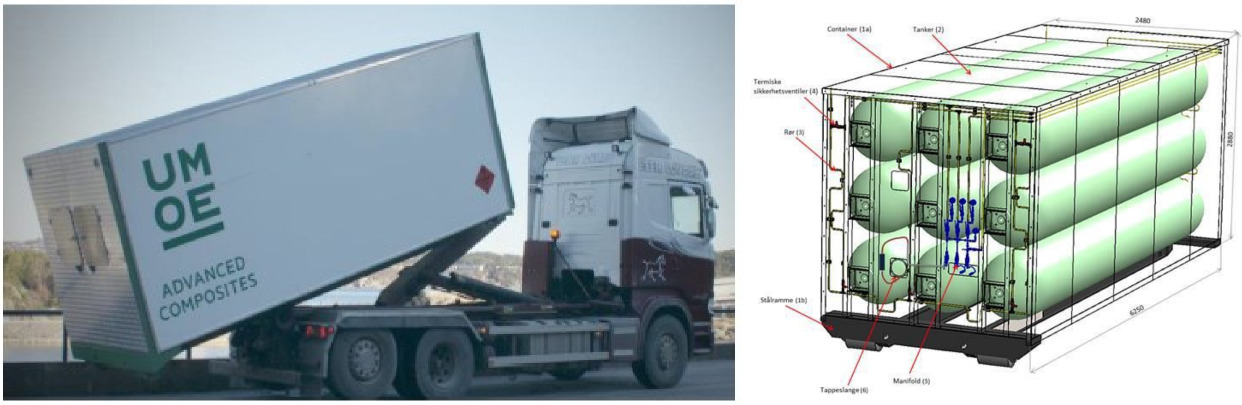

Figure 8: Trucking hydrogen vessel bundles from production site to usage sites is common for hydrogen transportation (UMOE Advanced Composites, 2017), (Suomilammi, 2018)

In the concrete area in front of the hydrogen plant, two large transport vessels can be placed. If the demand increases more than anticipated, the area will be expanded.

6.2. Plant Safety

The area around the hydrogen plant is divided into ATEX zones (ATmosphères EXplosibles) that are classified by how hazardous they are in regard to potential for an explosive atmosphere (Directive 2014/34/EU). In these zones special precautions must be made to prevent the risk of ignition which can cause fires and explosions. Equipment in ATEX zones must be classified as safe for use in hazardous areas. The electrolyser is in a defined ATEX container while the other container is a none-ATEX one. The none-ATEX container must be placed at least 2 meters away from the other container in case worst comes to worst (Health and Safety Executive, n.d.). Figure 9 shows a schematic view of the hydrogen plant where the ATEX zones are listed. The figure also visualises where the hydrogen transport vessels will be located.

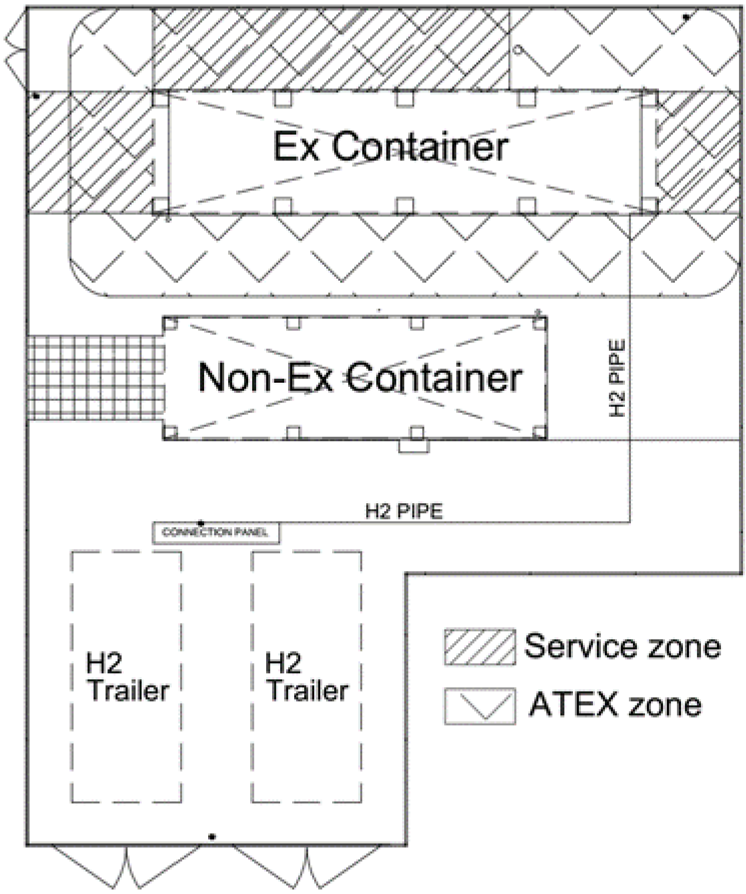

Figure 9: Schematic plan of the hydrogen plant at Hellisheidi

7. THE ELECTRICITY MARKET IN ICELAND

The electricity market in Iceland is unique, as power intensive industry uses 77,3% of all produced electricity. It is the reason why the electricity use per capita in Iceland is the highest amongst all nations in the world.

The highest peak in 2018 was 2.350 MW and average system utilization is close to 90%. Figure 10Figure 10**Error! Reference source not found.** below shows the annual energy consumption and forecasts for Iceland measured in GWh.

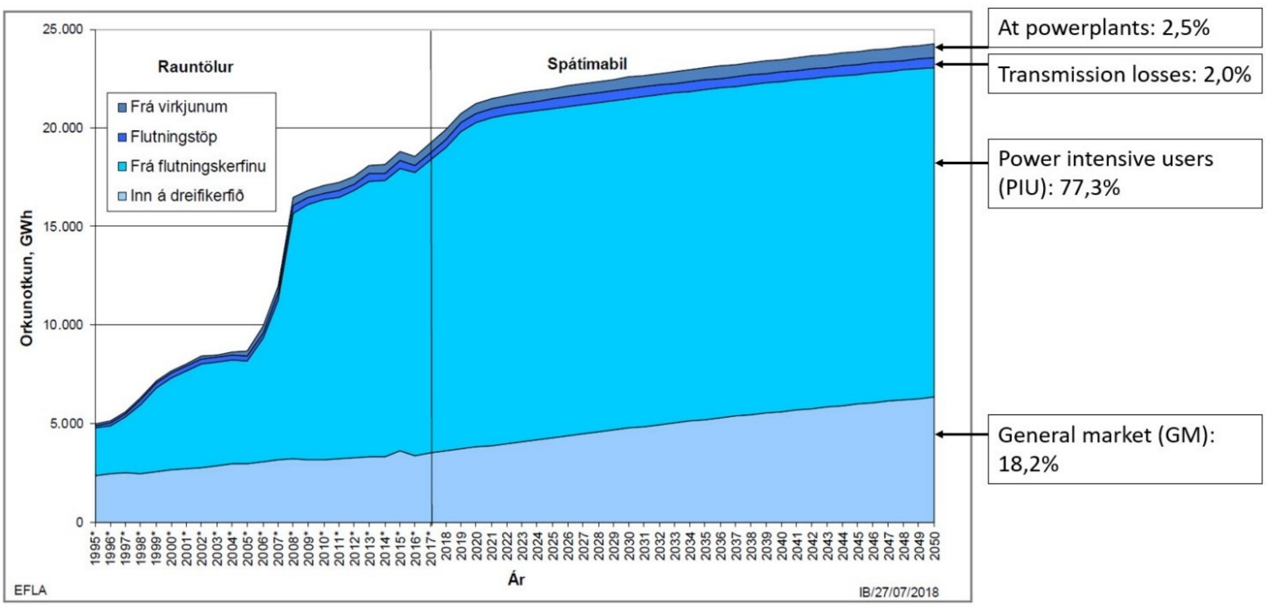

Figure 10: Energy consumption in Iceland (Orkuspárnefnd, 2018)

Electricity trading in Iceland has from 2005 been based on bi-lateral contracts between producers and sellers. The largest producer is Landsvirkjun which offer contracts with various conditions, mainly based on price, time, power and energy. The reason for Landsvirkjun's dominant position is due to the fact that flexible production is dominantly owned by them. The distribution of power plants and market share is estimated in Table 2 below.

Table 2: Annual production and estimated market share of Iceland's power producers (Hagfræðistofnun, 2018)

Producer	Hydropower TWh / year	Geothermal TWh / year	Total production TWh/year	PIU (est.)	GM (est.)
Landsvirkjun	13,46 (96%)	0,57 (11%)	14,02 (73%)	12,2 (79%)	1,9 (53%)
ON Power	0,03 (0%)	3,44 (67%)	3,47 (18%)	2,4 (16%)	0,7 (19%)
HS Orka	0,0 (0%)	1,16 (22%)	1,16 (6%)	0,7 (5%)	0,4 (11%)
Others	0,57 (4%)	0 (0%)	0,58 (3%)		0,6 (17%)
Total	14,06	5,17	19,23	15,3	3,6

On an hourly basis, Landsnet, Iceland's transmission system operator (TSO), operates a primary reserve market for fluctuations (± 40 MW balancing power) and a secondary reserve market (around 140 MW).

8. OPTIMISATION OF GEOTHERMAL POWER PRODUCTION

Production of hydrogen is mainly planned to take place during nights, especially during weekends. During these periods, the required load from the general market is at its lowest. The most frequent season of low-loads are during summer, when it is bright all day round, streetlights stay off and social activities are at its lowest. This can occur too during winter, for instance when outdoor temperature is high.

In the initial stages, the available power during nights will be higher than the installed electrolyser capacity. Additionally, in the beginning the demand for hydrogen is expected to be very modest and the energy required for the hydrogen production will be low.

A part of the H2ME project is the arrival of hydrogen powered buses on the streets of the capital. When those buses arrive, the demand will rise drastically, and the initial electrolyser will need to be switched on, more or less constantly. It is obvious that additional electrolyser(s) will be needed at that time. Demand Side Balancing (DSM) might be a way of sourcing energy for hydrogen production, but the applicability and guidelines for DSM are expected to be included in new grid codes from the TSO.

Figure 11 shows a typical energy consumption on the general market as well as the load covered with production from the geothermal plants during summer. The area between the base load and the low night load is the optimum time for hydrogen production. These are shown with black columns and highlight the available power for hydrogen production.

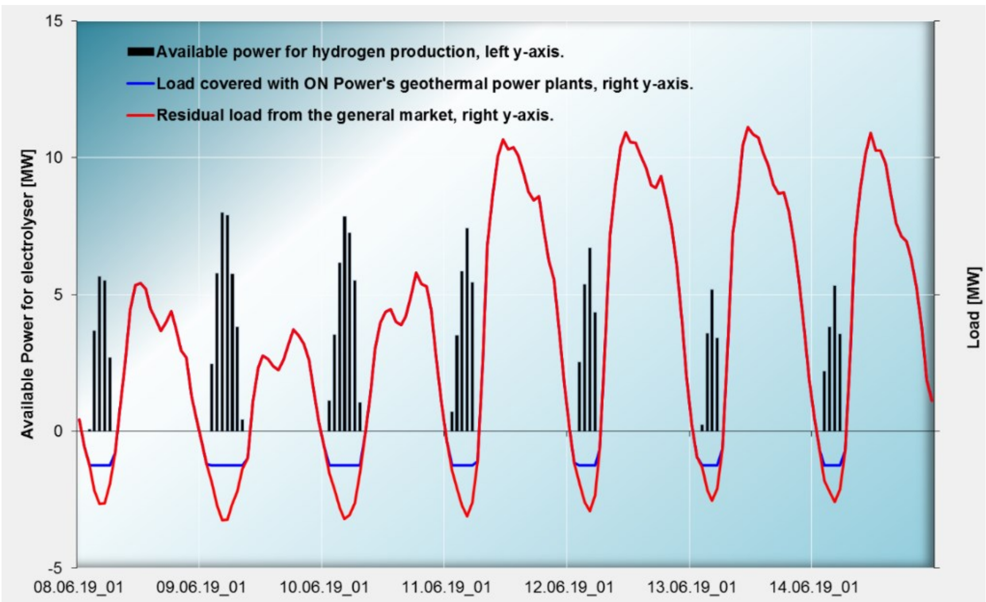

Figure 11: Typical weekly load profile for ON Power during summer

9. CHALLENGES

When encountering new challenges plans are typically in place to deal with unlikely events and mitigate their impacts. However, the domain of unforeseen challenges remains in place.

9.1. Electrical System Challenges – When or If?

Having hydrogen production on-site creates flexibility to deal with periods of low loads. The introduction of BEV might change the shape of the load curve as peak demand at evening times could increase. Having flexible hydrogen production with a lot of storage can contribute to flattening out the curve.

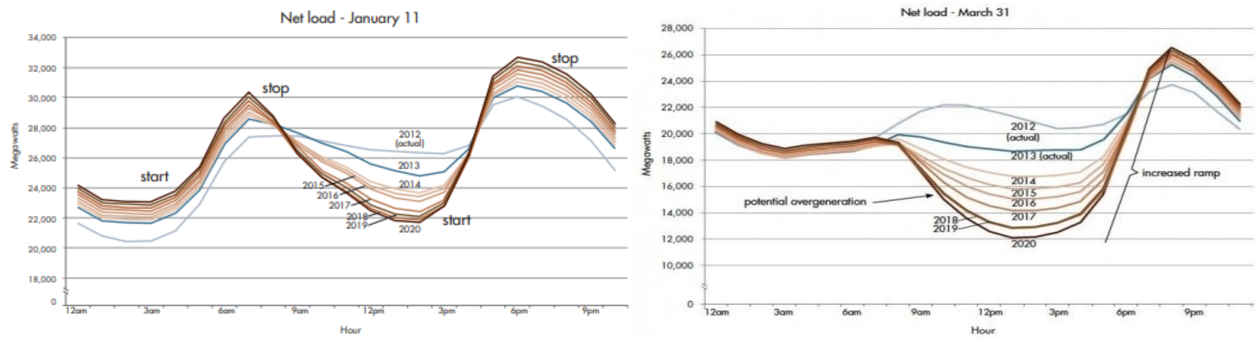

Figure 12: Real and forecasted daily load profiles in California during winter and spring, "duck curve" (Roberts, 2018)

California duck curve, as shown in **Error! Reference source not found.**, shows how fast residual loads can change with time. The large decrease during mid-day due to solar power may not be representative for Iceland, but evening peaks could be expected in Iceland, as well as in California as BEV ownership increases. The development of loads during nights could decrease also, at least short term, as light posts will use LED bulbs instead of traditional incandescent or nitrogen bulbs. Wind will likely cause challenges as well on the residual load in the system due to its inflexibility. Therefore, having hydrogen production on-site will increase the plants flexibility to deal with potential variable future loads while utilising the geothermal resource better.

9.2. On-Site Challenges

The Hellisheidi geothermal plant is designed as a relatively large combined heat and power plant, whereas the heat capacity will increase hand in hand with a growing population of the capital. Adding hydrogen production to the plant adds another degree of complexity to the on-site operation. Trucks are expected to come and pick up full vessels all year round and leave empty vessels to be re-filled. There are many challenges operating hydrogen production above 260 metres above sea level in Iceland. Weather at Hellisheidi can be very bad during wintertime, a lot of snow and wind. Ambient temperature can be constantly below 0°C. That can cause ice blocking in pipelines and other operational problems. To decrease the risk of ice blocking, pipelines are insulated, and a thermal cable is placed between the insulation and the pipelines. The purpose is to keep the pipelines temperature above 0°C. Ice and snow during the wintertime on the concrete floor may also cause problems and risks. This is especially dangerous for the drivers that will load and unload the hydrogen vessels for transportation to the filling stations. Therefore, it is essential to install an underfloor heating system to increase the safety.

9.3. Market Challenges / Market Development Challenges

The market development for alternatives to traditional petrol remains unclear. As of now, it seems that three fuel types are promising, synthetic natural gas (SNG), electricity and hydrogen. In addition to this, hybrid uses, where more than one source of fuel is used, may be a part to make the transition. The question is simply: Will customers favor hydrogen cars?

9.4. Unforeseen Challenges

On the 10th of June 2019 there was an explosion at the Kjørbo hydrogen refilling station located outside of Oslo, Norway. The preliminary results of the cause of the explosion is due to a leak in the plug of high-pressure vessels (Løkke, 2019). The plug in high-pressure vessels in Iceland are the same type as the one involved in this incident and hydrogen stations have been closed in Iceland for security reasons. The time of re-opening remains to be seen. Although this incident is not related to the electrolyser, sales of the end-product will be halted for an unforeseeable time. This incident will therefore slow down the start-up phase and commercial operations of the hydrogen production at Hellisheidi.

10. FUTURE THOUGHTS

The use of hydrogen in transportation is not new in Iceland. In 2003 the world's first hydrogen refilling station was opened in Reykjavík. During a period from 2003-2007 six hydrogen buses were operated in the streets of the capital, as well as a few cars (Ásmundsdóttir, 2008). However, due to a low demand of FCEVs the initial hydrogen station closed in 2011.

With increasing wind and solar production, hydrogen has gained a new momentum in Europe as it can play a role as energy storage when the demand is low, and supply is abundant. How the hydrogen will be utilized remains the key question. As of now, injection into the gas grid, energy storage (power to gas to power, P2G2P), methanisation by using a carbon dioxide source and using hydrogen as a fuel source in transportation are all promising.

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