ENERGY TRANSITION

Hydrogen production plant in Helguvík, Iceland.
An architectural approach to green industry

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Thank you

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Abstract

The energy transition in Iceland is of global significance. Supplementing fossil-fuels for sustainable energy where direct electricity does not apply, calls for major changes in energy infrastructure. Iceland is a perfect place to explore hydrogen production and utilization due to its abundant renewable energy sources, such as geothermal and hydroelectric. The architectural challenge lies in the relationship between the local communities and the big energy and industrial companies that need each other to thrive. Industrial structures and sites are usually quite universal in their own nature but architecturally the aforementioned relationship manifests in new industrial structures that are in a good dialogue with the local social and natural surroundings. This design research examines the potential of hydrogen production in Reykjanes, Iceland, for the purpose of utilizing clean energy technology specially to reduce flight and shipping emissions and then explores other uses, such as in land transport and exporting hydrogen to a global market. In addition, it will consider the social and spatial impact of a new eco-industrial park related to the hydrogen industry, in Helguvík, next to the town of Keflavík. By exploring the spatial qualities of the energy transition in Reykjanes, this design study provides valuable insight into the potential for utilizing hydrogen as a clean energy technology.

Can architects help with sustainable development?

This project is student driven, meaning that I personally decide what to design. What do I want to work on?
This called for a personal reflection. I had to ask myself the question: what really matters in life? My children are everything to me and as long as I am working on what matters to them and their generation my time is well spent. There are two things that I'm afraid threatens their generations' well being, one is external, the climate change, and the other internal, hopelessness. The project had to be about working on the issues of climate change with a positive attitude towards the future. Optimistic but realistic, beautiful but functional, breaking down barriers spatially and socially and building bridges instead.

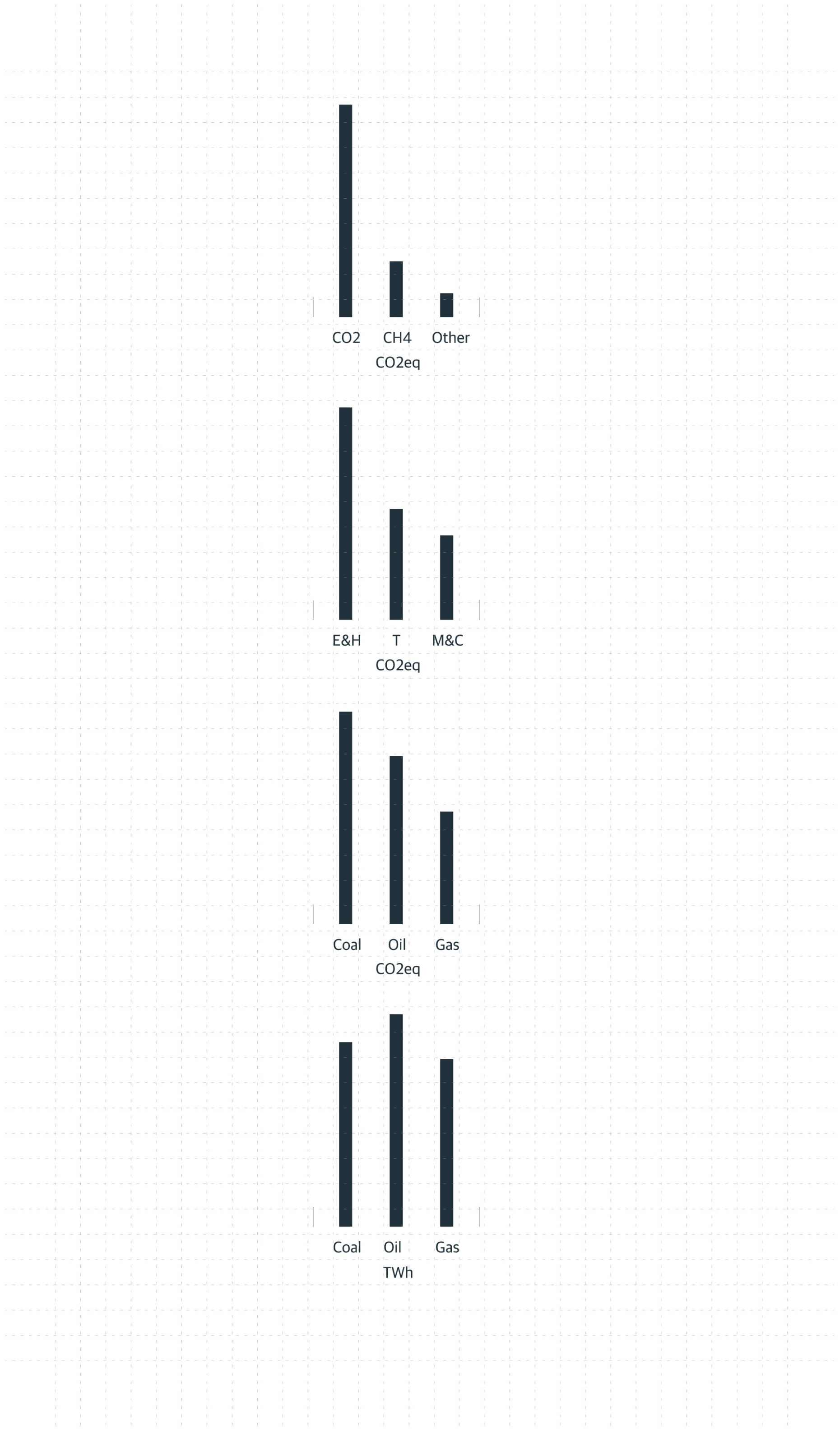
Climate change is an extremely complicated issue, but what kind of a project would be appropriate for a small Icelandic architecture student, and future practicing architect. I quickly learned that I don't need to make up new climate related issues to work on, there are plenty of them. The government has identified the key issues.[1] One issue that is likely to have a great effect on the built environment is the energy transition and the infrastructural and industrial changes needed to make the transition a reality. When I started to look at heavy industry and infrastructure I recognised that every decision made in that arena and every idea that is challenged could have huge effects. I had the feeling that architecture was underestimated and opportunities overlooked. At the same time I have never felt as vulnerable personally, as an architect and human being. The scale, highly profound engineering and corporational bigness of it all made me think if even architectural thinking was appropriate at all in this field. The question: can architecture help with sustainable development?, led me through the project. I asked the question in interviews to a variety of people and to myself frequently and the question lightened up a few problems that the project design responds to.

I recognize that this research shows only a narrow view on the subject, but I felt like I had to understand the view of the stakeholders and regulatory bodies to come up with a relevant response in the design. This paper includes research made to orient myself in a quite confusing world of climate actions. I try to narrow down the issues to end up with a real-world scenario as a design subject.

1 'Verkefnisstjórn aðgerðaáætlunar í loftslagsmálum, 'Aðgerðaáætlun í loftslagsmálum: Aðgerðir íslenskra stjórnvalda til að stuðla að samdrætti í losun gróðurhúsalofttegunda til 2030' (Reykjavík: Umhverfis- og auðlindaráðuneytið, June 2020).

1
energy and emission

Global Context
National Context



Energy and emission

Global Context

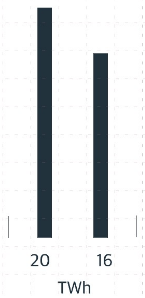
Climate change is a global issue. Unsustainable emissions of greenhouse gasses (GHG) are the cause of these changes. There are many types of gasses that have a greenhouse effect. These effects are measured with carbon dioxide equivalents (CO_2eq).[2] Of all greenhouse gasses, **carbon dioxide** is the largest contributor to global GHG emissions, accounting for around three-quarters (**74.4%**) of total emissions (2016).[3] This project is a counteract to the release of carbon dioxide (CO_2). Then the question is: what sectors release the most CO_2 worldwide? When we look at total CO_2 emissions by sector, electricity and heating dominate the chart, releasing 15.76 billion tons annually and following are transport (8.22 bt) and manufacturing and construction (6.25 bt.).[4] The reason why these sectors pollute as much as they do is that they are very energy demanding and still they depend heavily on fossil fuels. These fuels are coal, oil and natural gas. When it comes to energy transition we face a great challenge in supplementing **coal**, **oil** and **natural gas**[5] with zero emitting energy harvested in a sustainable way.

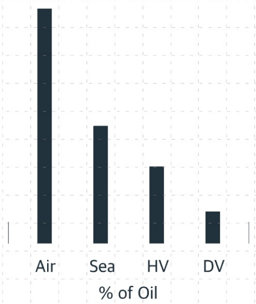
2 'Glossary:Carbon Dioxide Equivalent', accessed 11 April 2023, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent.

3 Hannah Ritchie, Max Roser, and Pablo Rosado, 'CO2 and Greenhouse Gas Emissions', Our World in Data, 11 May 2020, https://ourworldindata.org/greenhouse-gas-emissions.

4 Hannah Ritchie, Max Roser, and Pablo Rosado, 'CO2 and Greenhouse Gas Emissions', Our World in Data, 11 May 2020, https://ourworldindata.org/emissions-by-sector.

5 'CO2 Emissions by Fuel or Industry', Our World in Data, accessed 11 April 2023, https://ourworldindata.org/grapher/co2-emissions-by-fuel-line.





Energy and emission

National Context

Icelanders use mainly three energy carriers, heat, electricity and fossil fuels of which are mainly oil and petrol.[6] When we look at primary energy use in Iceland over the years, Iceland does **not follow** the world chart when it comes to CO2 emissions **in electricity and heating**.[7] The reason is the accessibility to geothermal waters and previous investments in geothermal and hydropower-plants.

According to the governance charter the Icelandic government has made an ambitious goal in energy transition in all areas. "The goal is to achieve carbon neutrality and full energy conversion no later than **2040**" and the tone is set with the following political statement: "The government will not issue any licenses for oil exploration in Iceland's exclusive economic zone."[8]

Because the nation has to import all of its oil it's quite easy to draw up a simple picture of the problem of the energy transition. The production of renewable energy in Iceland needs to meet the amount of energy that would otherwise be imported in the form of fossil fuels. CO2 emissions come mainly from **fishery and transportation**, that includes tourism and transportation of goods. Of the about one million tonnes of oil imported[9], 52% goes on airplanes, 26% on ships, 15% on heavy vehicles and 7% on domestic vehicles.[10] It is estimated that at least **16twh** are needed to meet these energy demands with electricity.[11] The total energy production is **20 twh** now and 78% of that is used in heavy industries.

If we look closer at flights, in 2018 Icelanders ranked as the highest emitters per capita with 3.5 tons, next comes Qatar with 2,5[12] tons, when the world average is only 98 kg.[13] The tourism industry is of course a large part of the economy of Iceland so it is hard to say where the responsibility lies. However, when these figures have been adjusted for tourism it is estimated that the average Icelander contributed more than 1 ton 2018 as the 3rd highest contributor per person.[14]

Every year The National Energy Authority of Iceland (NEAI) recalculates the energy forecast for the upcoming years. Now the forecast states that in 2030 all new registered personal cars will be electric and in 2040 all heavy vehicles also. In 2030 5% of fuels used in international flights will be renewable and in 2050, 50% of fuels used in international flights and on all ships will be renewable. The agency also broadcast a scenario where as much renewable fuels are produced in Iceland as are used there the year 2050.[15] According to a governmental report published in 2022 Iceland is likely to add **100mw annually** to the electric grid the next 20-30 years to meet the energy transition[16], this is equivalent to one Reykjanesvirkjun per year. Where direct use of electricity does not apply, other energy carriers are necessary.

6 'Orkuskipti', accessed 12 April 2023, https://orkuskipti.is/.

7 'Orkutölur 2004-2021', Orkustofnun, accessed 12 April 2023, https://orkustofnun.is/orkustofnun/utgafa/orkutolur/.

8 'Stjórnarsáttmáli', accessed 16 April 2023, https://www.stjornarradid.is/rikisstjorn/stjornarsattmali/.

9 Orkuspárnefnd, 'Eldsneytisspá 2021-2060' (Reykjavík: Orkustofnun, September 2021), 8.

10 'Orkuskipti'.

11 Umhverfis- orku- og loftslagsráðuneytið, 'Staða og áskoranir í orkumálum með vísan til markmiða og áherslna stjórnvalda í loftslagsmálum' (Reykjavík: Stjórnarráð Íslands, March 2022), 14.

12 'Where in the World Do People Have the Highest CO2 Emissions from Flying?', Our World in Data, accessed 9 May 2023, https://ourworldindata.org/carbon-footprint-flying.

13 Sola Zheng, 'Not Every Tonne of Aviation CO2 Is Created Equal', International Council on Clean Transportation (blog), 16 October 2019, https://theicct.org/not-every-tonne-of-aviation-co2-is-created-equal/.

14'Where in the World Do People Have the Highest CO2 Emissions from Flying?'

15 'Endurreiknuð raforkuspá', Orkustofnun, accessed 12 April 2023, https://orkustofnun.is/orkustofnun/frettir/endurreiknud-raforkuspa.

16 Umhverfis- orku- og loftslagsráðuneytið, 'Staða og áskoranir í orkumálum með vísan til markmiða og áherslna stjórnvalda í loftslagsmálum', 13.

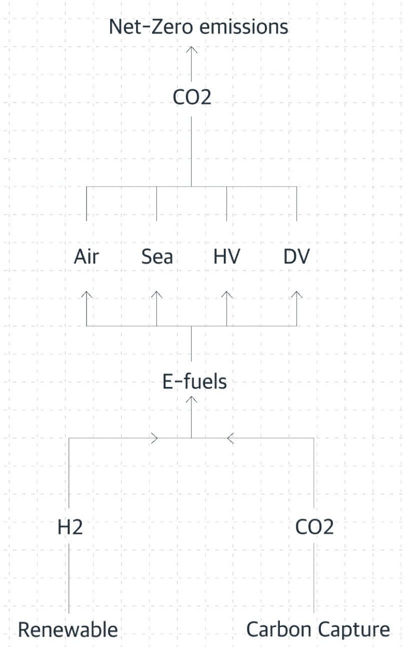
Energy and emission

National Context

When it comes to a technical response to CO_2 emissions there is a lot of work needed in developing solutions that meet future demands for renewable fuels in Iceland. When we look at the bigger picture, Icelanders have the option to sell green energy on the world market. That might have a larger direct effect on the climate than focusing only on what is used nationally. All energy that theoretically can be produced in Iceland and even more, could be consumed instantly by the world, but no matter how "green" the energy production gets, there will always be **sacrifices**. How willing is the nation to sacrifice its unique nature to contribute to the world's fight against CO_2 emission? That will remain a political question that I'm going to set aside for now. There is another relevant option that is worth mentioning here and that is to focus on being sufficient in sustainable energy and invest in entrepreneurship and knowledge that could be used in an exemplary fashion for other parts of the world. There will not be one way forward and both ways are being done now to some extent.

2
E-fuels

Global Context
National Context



E-fuels

We have talked about a mature increase of electricity to the grid to meet the energy transition. That raises the question of how the electricity will be transmitted where it is most needed to substitute oil. As described earlier the National Energy Authority predicts that land vehicles large and small will go fully electric in the near future.[17] We are all aware of the rapid development of electric cars in recent years and many predict that the urban sector will eventually go 100% electric mainly because of efficiency reasons.[18] This will only solve a part of the problem. Airplanes and ships consume most of the oil imported and there is more uncertainty in these fields. Until we see new ships and planes run with zero emission as technological innovations promise, the existing fleet can run on **CO2-neutral** fuels (e-fuels) without any mature changes to existing vessels or infrastructure. E-fuels (where E stands for electric) are fuels where energy from renewable electricity is stored in liquid or gaseous form and the fuel becomes the energy carrier.

> *"Depending on the form or the e-fuel required, either a Power-to-Gas or Power-to-Liquid process is used. Both of these production processes involve two or three phases, with first of all hydrogen (H2) production by water electrolysis from renewable electricity, associated with another molecule - CO2 for e-crude and synthetic methane or methanol, or nitrogen (N2) for synthetic ammonia. Synthetic crude oil must be refined (like fossil oil) to produce synthetic kerosene or diesel.*
> *E-methane, e-methanol, e-diesel and e-kerosene are synthetic [**hydrocarbons**], so their production processes require CO2. This vital element can either be captured directly from the atmosphere or taken from industrial plants that use fossil fuels."* [19]

Because of newly implemented regulations and economic incentives in the EU,[20] CO2 from industries in Europe are likely to be imported in large amounts to Iceland to be stored underground. This opens up opportunities for other utilizations of CO2 in Iceland like production of synthetic fuels (e-fuels). E-amonia, e-methanol, and e-crude oils are all hydrogen-based fuels that are suitable for **ships** and are likely to play a big part in the transition of that sector internationally.

"Today nearly 30% of sea freight volumes is dedicated to transporting of fossil fuels."[21] Bureau Veritas consultants made a whitepaper for the International Maritime Organization, with the title "Alternative Fuels outlook for shipping" there they describe how important it is for future marine transport to have access to upstream green energy close to the harbors due to lower density of alternative green fuels. Alternative fuels like hydrogen, ammonia and methanol, take on average three times more space than oil. This means that electricity and fuel demands will increase a lot around the main shipping routes.[22]

The act of making E-kerosine (**aviation** fuel) is in many ways similar to the conventional fossil fuel industry. This industry is without a doubt environmentally daring and I assume that the processes needed to produce aviation fuels would be controversial. If Icelanders decide to be energy independent, and still continue to use the existing aviation and maritime infrastructure and fleet, this industry is needed.

17 'Endurreiknuð raforkuspá'.

18 Stefan Pischinger, 'Synthetic Fuels', MTZ Worldwide 80, no. 5 (1 May 2019): 80–80, https://doi.org/10.1007/s38313-019-0040-1.

19 '| ENGIE', Engie.com, accessed 13 April 2023, https://www.engie.com/en/news/e-fuels-what-are-they.

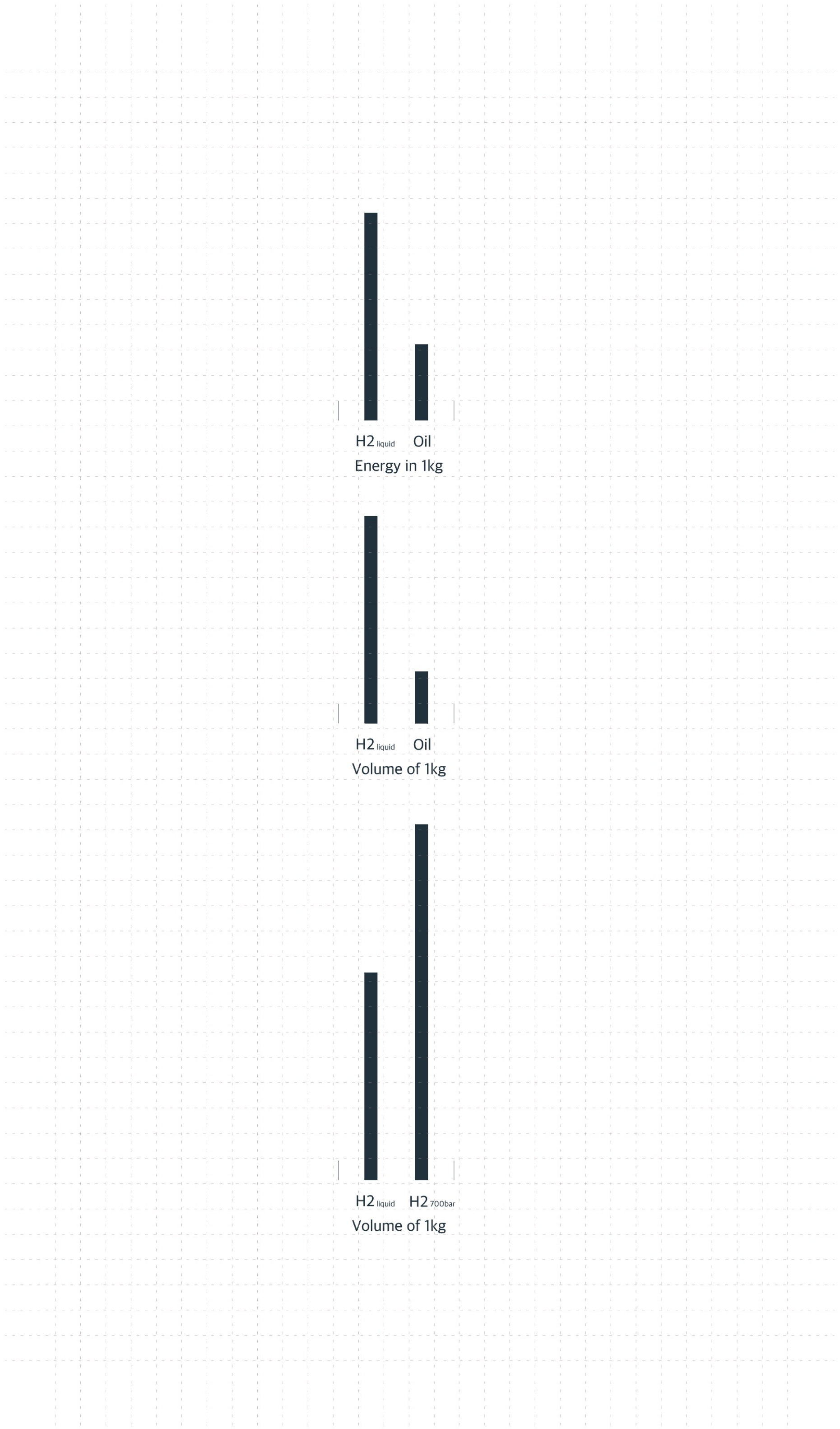
20 'Carbon Capture, Use and Storage', accessed 14 April 2023, https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage_en.

21 Bureau Veritas, 'Alternative Fuels Outlook for Shipping: An Overview of Alternative Fuels from a Well-to-Wake Perspective', White Paper, September 2022, 8.

22 Bureau Veritas, 9.

3
Hydrogen

The Element
Short History - Global Context
Industrial Scale - Global Context



Hydrogen

Discerning readers notice that hydrogen serves as a key element in the e-fuels business. Based on the last chapter hydrogen will play an essential role in the transition because hydrogen is needed as a fundamental element of the making of **hydrocarbons**. The fact is that when pure hydrogen burns (reacts with oxygen from the atmosphere) only water is formed (H_2O) whereas when the hydrocarbon chains burn the oxygen reacts to the hydrogen atom and then all carbon atoms following in the chain and CO_2 is formed as a consequence of that. It is quite compelling to imagine a future where we can get rid of the carbon (C) from the whole equation and utilize hydrogen in its pure form instead.

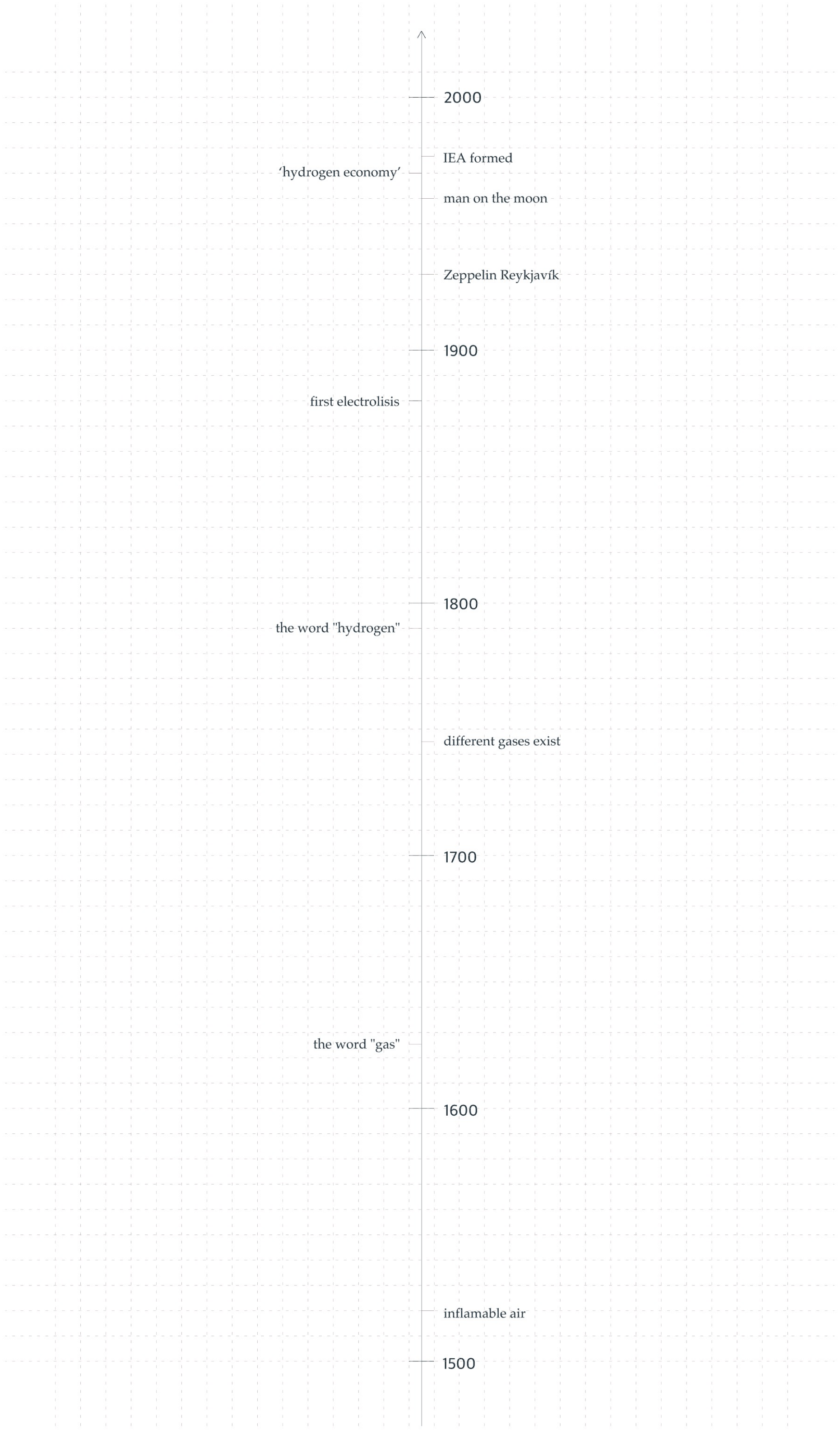
The Element

Hydrogen (H) is the first element in the periodic table. It is the most abundant element in the universe. It is in gaseous molecular form (H_2) in standard conditions. It is colorless, odorless, tasteless, non-toxic, and highly combustible. “On a **mass basis**, hydrogen has nearly three times the energy content of gasoline—120 MJ/kg for hydrogen versus 44 MJ/kg for gasoline. On a **volume basis**, however, the situation is reversed; liquid hydrogen has a density of 8 MJ/L whereas gasoline has a density of 32 MJ/L[.]”[23]

“Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires **high-pressure** tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is -252.8°C.”[24]

23 ‘Hydrogen Storage’, Energy.gov, accessed 2 April 2023, https://www.energy.gov/eere/fuelcells/hydrogen-storage.

24 ‘Hydrogen Storage’.



Hydrogen

Short History - Global Context

At the beginning of the sixteenth century, it was discovered that gas ("inflammable air") was formed during the reaction between sulfuric acid and iron.[25] At the beginning of the seventeenth century the word "gas" was first introduced[26] and in the mid eighteenth century Joseph Black confirmed that different gasses existed.[27] In 1788, Antoine Lavoisier gave the aforementioned gas, hydrogen its name (Gk: hydro = water, genes = born of). Hydrogen was used in balloons and airships in the 18th and 19th centuries, and it helped humans reach the moon in the 1960s by fueling rockets.[28]

The term '**hydrogen economy**' was first coined in 1970 by John Bockris[29] and has been considered and discussed ever since. In most cases it is discussed as a complement to traditional energy vectors in a context of a smart and low carbon strategy for specific applications and locations.[30] In 1974 the International Energy Agency (IEA) was established in response to the global oil market disruptions.[31] The IEA has published a report yearly "that tracks hydrogen production and demand worldwide, as well as progress in critical areas such as infrastructure development, trade, policy, regulation, investments and innovation."[32]

25 Furat Dawood, Martin Anda, and G. M. Shafiullah, 'Hydrogen Production for Energy: An Overview', International Journal of Hydrogen Energy 45, no. 7 (7 February 2020): 3850, https://doi.org/10.1016/j.ijhydene.2019.12.059.

26 'Tryals and Tribulations', Science History Institute, 16 October 2015, https://www.sciencehistory.org/distillations/tryals-and-tribulations.

27 'Timeline of Hydrogen Technologies', in Wikipedia, 18 April 2023, https://en.wikipedia.org/w/index.php?title=Timeline_of_hydrogen_technologies&oldid=1150418005.

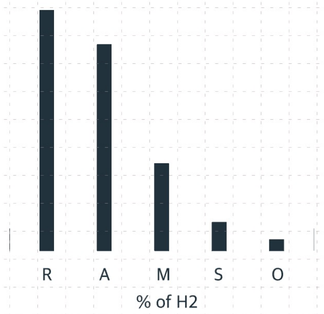
28 Dawood, Anda, and Shafiullah, 'Hydrogen Production for Energy', 3850.

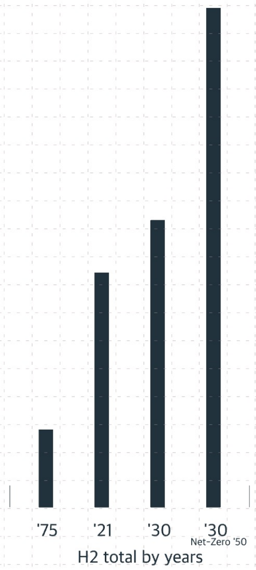
29 Dawood, Anda, and Shafiullah, 3851.

30 Dawood, Anda, and Shafiullah, 3852–53.

31 'Mission - About', IEA, accessed 4 May 2023, https://www.iea.org/about/mission.

32 'Global Hydrogen Review 2022 – Analysis', IEA, accessed 4 May 2023, https://www.iea.org/reports/global-hydrogen-review-2022.





Hydrogen

Industrial Scale - Global Context

Hydrogen has been used in large quantities for industrial use for a long time. The industrial sector is the **leading consumer** of hydrogen. Hydrogen is used in refineries, the chemical industry and steelmaking. Hydrogen has played a crucial role in the production of ammonia fertilizer, helping to feed the world's growing population.[33]

About 42% of the hydrogen around the world goes in refining of oil; 36% is used in ammonia production; and about 15% is used to produce methanol; about 5% goes to the steel industry. Other applications only account for only about 2%."[34] Today, supplying hydrogen to industrial users is a major global business, and demand for it has increased more than threefold since 1975. In 2021 the demand for pure hydrogen is about 70 million tonnes per year and 94 million tonnes total when methanol and other mixed use is counted.[35] **Only 1%** of hydrogen produced today worldwide is **renewable** and the rest is produced from fossil fuels.[36] "Low-emissions hydrogen production worldwide in 2021 was less than 1 million tonnes – with practically all of it coming from [power]plants using fossil fuels with **carbon capture**, utilisation and storage."[37] 6% of all natural gas and 2% of all coal usage is devoted to hydrogen production. Consequently, the production of hydrogen is responsible for emitting approximately 830 million tonnes of carbon dioxide per year (2019), which is equal to the combined CO_2 emissions of Indonesia and the United Kingdom. In energy terms, the total global annual demand for hydrogen is around 330 million tonnes of oil equivalent (Mtoe), which is more significant than Germany's primary energy supply. [38]

> *Considering policies and measures that governments around the world have already put in place, we estimate that hydrogen demand could reach 115 Mt by 2030, although less than 2 Mt would come from new uses. This compares with the 130 Mt (25% from new uses) that would be needed to meet existing climate pledges put forward by governments around the world so far, and with nearly 200 Mt needed by 2030 to be on track for net zero emissions by 2050.*[39]

To conclude, most of the hydrogen produced in the world is **CO_2 emitting** and if the climate pledges are to be fulfilled there is a tremendous need for "green hydrogen" in the industrial market. Action is needed now to answer this demand.

33 International Energy Agency, 'The Future of Hydrogen: Seizing Today's Opportunities', June 2019, 17, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

34 'Hydrogen – Analysis', IEA, accessed 9 May 2023, https://www.iea.org/reports/hydrogen.

35 International Energy Agency, 'The Future of Hydrogen', 17.

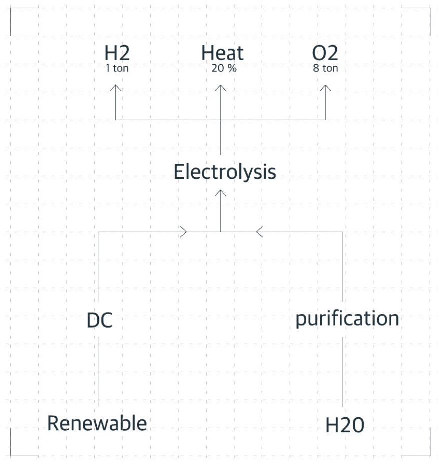
36 'How Much Will Renewable Hydrogen Production Drive Demand for New Renewable Energy Capacity by 2027? – Analysis', IEA, accessed 2 May 2023, https://www.iea.org/reports/how-much-will-renewable-hydrogen-production-drive-demand-for-new-renewable-energy-capacity-by-2027.

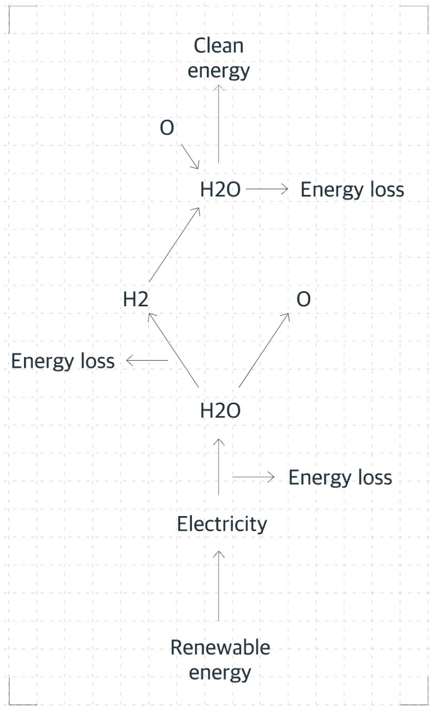
37 'Promising Signs in Electrolyser Manufacturing Add to Growing Momentum for Low-Emissions Hydrogen - News', IEA, accessed 6 May 2023, https://www.iea.org/news/promising-signs-in-electrolyser-manufacturing-add-to-growing-momentum-for-low-emissions-hydrogen.

38 International Energy Agency, 'The Future of Hydrogen', 17.

39 'Executive Summary – Global Hydrogen Review 2022 – Analysis', IEA, accessed 20 April 2023, https://www.iea.org/reports/global-hydrogen-review-2022/executive-summary.

4
Green Hydrogen





Green Hydrogen

Production & methods

‘Green hydrogen’, also known as ‘renewable hydrogen’, is produced by using green energy sources such as **renewable energy** (solar, wind, **geothermal**, tidal, wave, ocean thermal, **hydro**, biomass), nuclear energy or energy recovery (recovered industrial heat, landfill gas, wastes that can be incinerated etc). There are several methods to produce ‘green hydrogen’ but here we will only discuss one of them, **water electrolysis**, where water is decomposed into O2 and H2 with electricity.[40] This method has gained increased attention as it offers a carbon-neutral alternative to traditional hydrogen production methods.[41] The process of using electricity to decompose water into oxygen and hydrogen gas by electrolysis has been known for well over 200 years.[42]

In simple terms in a water electrolyzer hydrogen power plant, the **inpu**t is **electricity** and **water** and the **output** is **H2**, **heat**, and **O2**, which is an important fact when we look at it in relation to ‘circular economy’ and the planning of ‘eco-industrial parks’

Electrolysis process requires only electricity and clean water; the devices that perform the electrolysis process are called electrolyser stacks. Electrolyzer stacks are made of a row of cells that each have a membrane. This membrane separates the H2 from O in the H2O compound (water) that surrounds it. Direct current (**DC**) is used to power the electrolysers, which involves two electrodes, one positively charged and one negatively charged. The hydrogen is collected at the negative electrode, while oxygen is collected at the positive electrode. Big scale productions of green hydrogen typically use multiple electrolyser stacks. The produced hydrogen is then purified, compressed, and stored in tanks. The electrolyzers operate on a 70 to 90 degrees celsius and because of that there is about **20%** energy that gets lost in heat. The weight ratio of Hydrogen and Oxygen is 1(H):8(O) that means that for each ton that is produced of hydrogen, **8 tons of oxygen** is made as a byproduct.

There are four water electrolysis systems that can be used in hydrogen production, alkaline (ALK), polymer electrolyte membrane (PEM), anion exchange membrane (AEM) and solid oxide water electrolysis.[43] All of these systems have **similar space requirements.** And the main differences are their material properties. The first one mentioned, alkaline technology is well established and has been on the market for a long time and PEM has several advantages over the other systems.[44] According to recent studies on these systems and the renewable energy sources available it is most cost effective to use hydroelectric power with PEM water electrolysis.[45] In addition, because of a higher operating current density of the system, balancing PEM electrolyzer plants is much simpler which is more attractive for **industrial applications**, or big scale production.[46]

40 Ibrahim Dincer, ‘Green Methods for Hydrogen Production’, International Journal of Hydrogen Energy 37 (n.d.): 1955–57.

41 ‘Hydrogen Production: Electrolysis’, Energy.gov, accessed 3 May 2023, https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

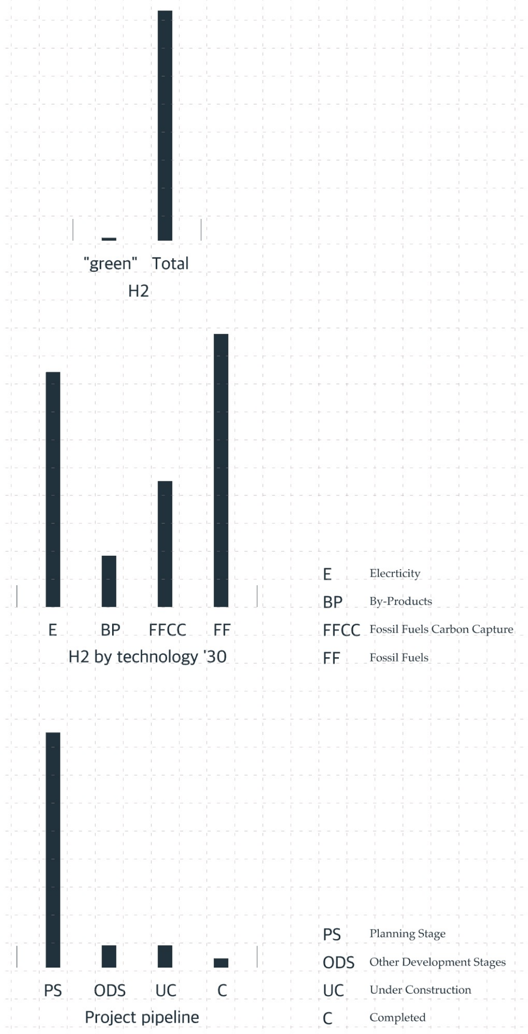
42 ‘THE HISTORY OF HYDROGEN | AltEnergyMag’, accessed 3 May 2023, https://www.altenergymag.com/article/2009/04/the-history-of-hydrogen/555/.

43 Mohd Nur Ikhmal Salehmin et al., ‘High-Pressure PEM Water Electrolyser: A Review on Challenges and Mitigation Strategies towards Green and Low-Cost Hydrogen Production’, Energy Conversion and Management 268 (15 September 2022): 1, https://doi.org/10.1016/j.enconman.2022.115985.

44 ‘Salehmin et al., 1

45 Salehmin et al., 18.

46 Jun Chi and Hongmei Yu, ‘Water Electrolysis Based on Renewable Energy for Hydrogen Production’, Chinese Journal of Catalysis 39, no. 3 (1 March 2018): 392, https://doi.org/10.1016/S1872-2067(17)62949-8.



Green Hydrogen

Global Context

IEA published a report after the G20 conference in Japan 2020. There they identify four near-term opportunities, focusing on the **real-world actions** that could help hydrogen achieve the necessary scale to bring down costs. Those **four opportunities** are the following: "1. Make industrial ports the nerve centres for scaling up the use of clean hydrogen. [...] 2. Build on existing infrastructure, such as millions of kilometres of natural gas pipelines. [...] 3. Expand hydrogen in transport through fleets, freight and corridors. [...] 4. Launch the hydrogen trade's first international shipping routes. [...] International co-operation is vital to accelerate the growth of versatile, clean hydrogen around the world."[47] In addition, one of the key recommendations from IEA to help governments and companies enable hydrogen to fulfill its long term potential is to "[m]ake the most of existing industrial ports to turn them into hubs for lower-cost, lower-carbon hydrogen."[48]

The latest Global Hydrogen Review of IEA published in 2022 includes a special focus on how Russia's invasion of Ukraine has accelerated a momentum behind hydrogen to enhance energy security.

> *"It is a policy plan to significantly reduce consumption of fossil fuels in the European Union to reduce reliance on fossil fuel imports from Russia and to accelerate the EU Green Deal. Along with energy efficiency provisions and scaling up other non-fossil fuel energy sources, the plan aims for 10 Mt/year of renewable hydrogen to be produced in the European Union and a further 10 Mt/year to be imported by 2030, where renewable hydrogen is defined as electrolytic hydrogen produced using renewables-based electricity."*[49]

Countless studies show that green hydrogen can be supplemented with natural gas in existing gas infrastructures and networks. Depending on individual networks, their conditions and makeup, 5%-20% hydrogen can be added to the networks with minimal changes. This could play a vital role to bring down CO2 emissions and support energy independence.

"[I]nvestor and developer **interest** in **low-carbon hydrogen** production facilities has **increased strongly**".[50] As of February 23 there are over 430 projects in the pipeline with green projects exhibiting clear dominance.[51] In the Hydrogen Projects Database gathered and published by IEA there are two Icelandic projects seen on this list, ECTOS (Nýorka 2003-2007) and George Olah Renewable Methanol plant in Svartsengi (2010-2011).[52] Both these projects are not currently operating. We know this is not an exhaustive list because it does not seem to include serious projects that are taking place in Iceland right now.

47 International Energy Agency, 'The Future of Hydrogen', 15.

48 International Energy Agency, 16.

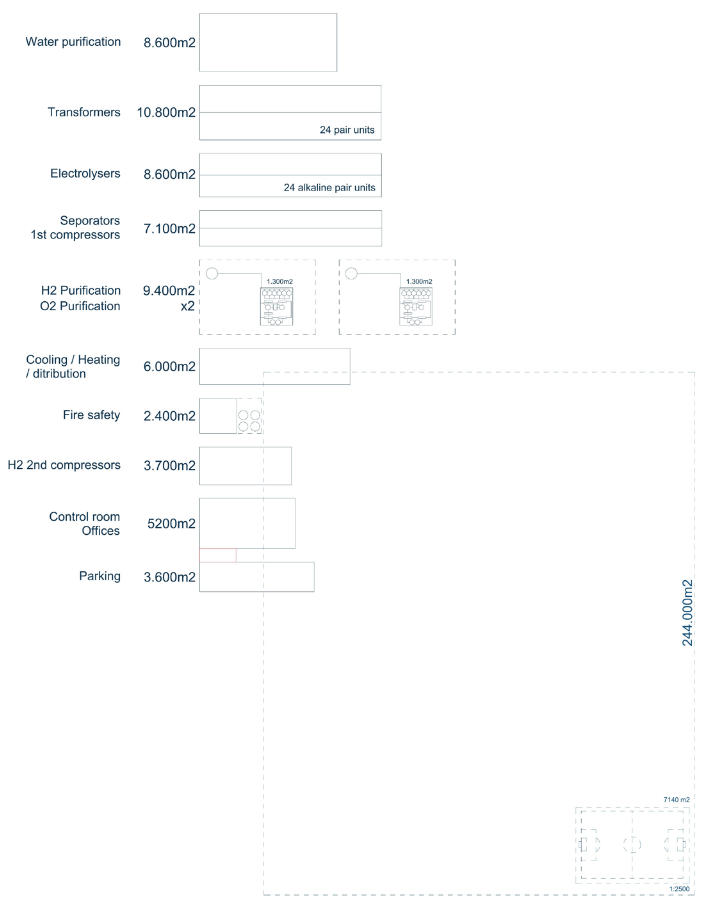
49 International Energy Agency, 'Global Hydrogen Review 2022' (IEA Publications, September 2022), 173.

50 'Global Low-Carbon Hydrogen Project Pipeline: Low-Risk Markets Experience More Development Success Amid A Globally Growing Pipeline', accessed 7 May 2023, https://www.fitchsolutions.com/power/global-low-carbon-hydrogen-project-pipeline-low-risk-markets-experience-more-development-success-amid-globally-growing-pipeline-28-02-2023..

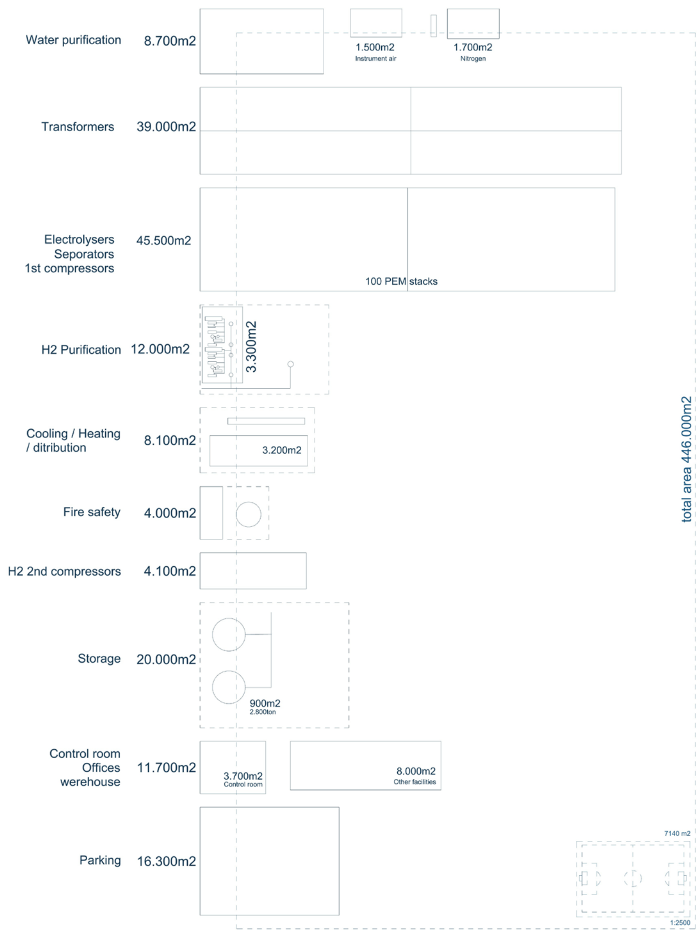
51 'Global Low-Carbon Hydrogen Project Pipeline: Low-Risk Markets Experience More Development Success Amid A Globally Growing Pipeline'.

52 International Energy Agency, 'Hydrogen Projects Database', 2021.

1Gw Hydrohub



1GW Plug & McDermot



Green Hydrogen

Global Context

Here are some quick spatial studies of two conceptual demonstration projects in the making. One is in Europe, an ongoing design by the Institute for Sustainable Process Technology (ISPT) and the other one is in the US put forward by the companies Plug and McDermot. Both these projects are demonstrations of **1GW green hydrogen plants**. This scale is considered as a desirable goal to have a remarkable impact on the energy market. To put this into perspective, in the feasibility study for hydrogen production at Grundartangi it is considered that E-fuel production needs to start at 100 - 300 MW scale to gain necessary size-efficiency.[53] There have been ideas of a 300mw green hydrogen plant in Helguvík that could have an annual production capacity of 40.000 tons.[54]

53 Aðalheiður Kristinsdóttir, Bjarni Már Júlíusson, and Hallmar Halldórs, 'Fýsileiki þess að framleiða rafeldsneyti á Íslandi' (Unnið af Ice Fuel fyrir hönd Grundartanga ehf, June 2021), 35.

54 'Vilja reisa vetnisverksmiðju í Helguvík með framleiðslugetu upp á 40 þúsund tonn', Kjarninn, 18 July 2022, https://kjarninn.is/frettir/vilja-reisa-vetnisverksmidju-i-helguvik-med-framleidslugetu-upp-a-40-thusund-tonn/.

Green Hydrogen

National Context

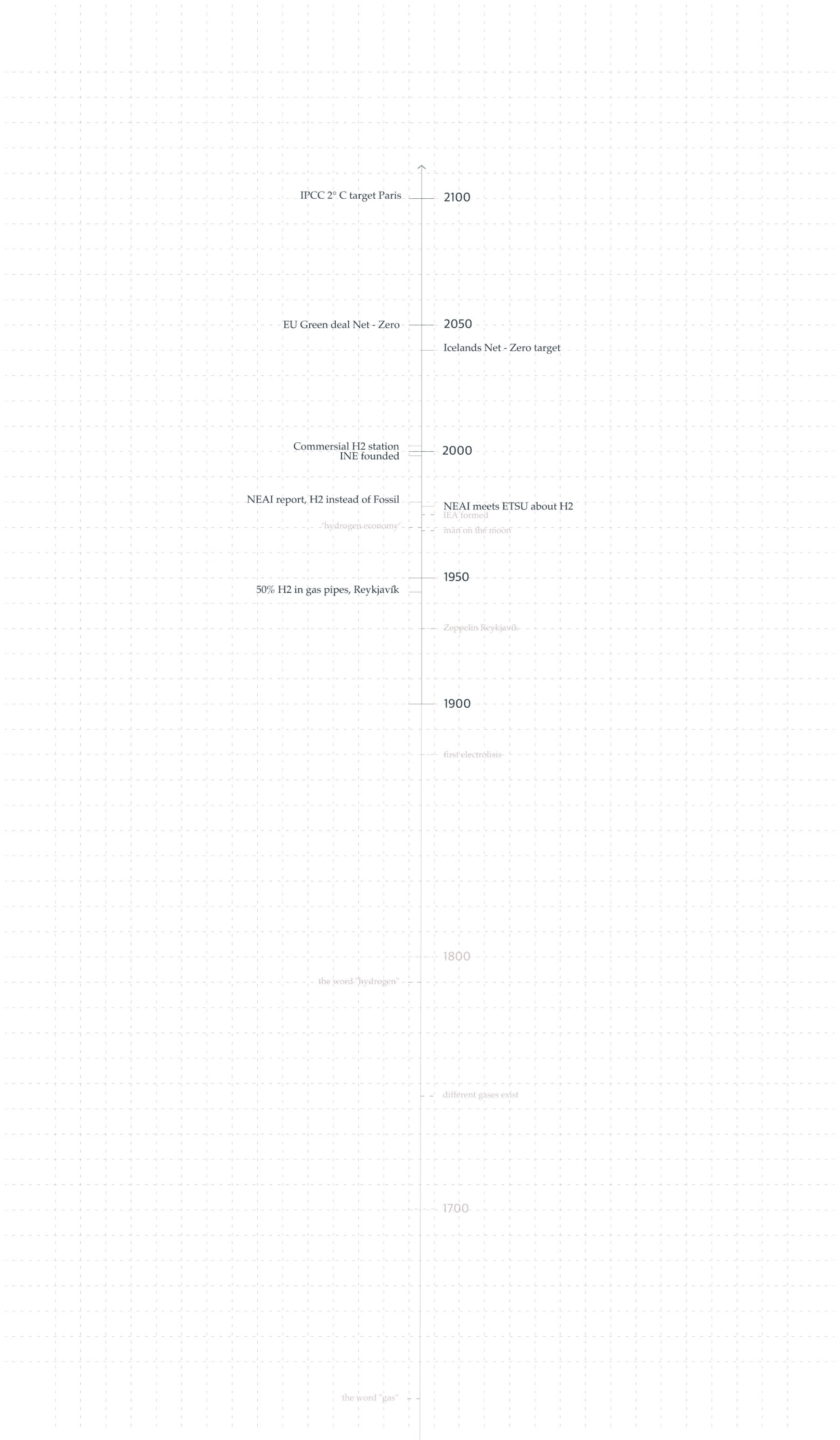
In April, 1979 Jón Steinar Guðmundsson as a representative of The National Energy Authority of Iceland (NEAI) visited Dr. K.F.Langley and Mr. K.Linacre from the Energy Technology Support Unit (ETSU) in Harwell, an agency within the Department of Energy in the UK. Guðmundsson was there to gather information for a research regarding hydrogen fuel production in Iceland. There they discussed the relevancy of implementing '**the hydrogen economy**' ideology. They agreed on that to be a distant dream and not applicable until 'late next century'. As importantly they mention a major energy shortage in the year 2025.[55]

The following year, **1980**, NEAI in a collaboration with the Faculty of Science at the University of Iceland released the report Hydrogen and hydrogen compounds: production and possible use instead of imported fuel (orig. Vetni og vetnissambönd: Framleiðsla og hugsanleg notkun í stað innflutts eldsneytis). Expectations and concerns that are seen in this report are strangely similar to those of today when it comes to energy shortage, energy independence, climate change and pollution, and how hydrogen could play a key role as a clean future fuel to meet these challenges. The author Bragi Árnason (1937-2019) points out that until the end of WWII, homes in Reykjavík used gas that contained 50% of hydrogen for cooking with good results as in both Europe and USA.[56] Árnason was a leading figure in Iceland in the exploration of hydrogen and published countless studies of that subject. The history of hydrogen research in Iceland and development of 'green hydrogen' could be read through his work.

The question might be asked why we haven't established the production of 'green hydrogen' already since these researches and notions were already happening **43 years ago**. We know that with the technology of the time (around 1980) it would not have been economically feasible. I also think the answer lies in the lack of government support and public entails about climate change back then.

55 Jón Steinar Guðmundsson, 'Vetni, grómun og kísill: Ferð til Bretlands í mars/apríl 1979' (Reykjavík: Orkustofnun: Jarðhitadeild, May 1979), 15, https://orkustofnun.is/gogn/Skyrslur/1979/OS-79021-JHD10.pdf.

56 Bragi Árnason, 'Vetni og vetnissambönd: Framleiðsla og hugsanleg notkun í stað innflutts eldsneytis' (Reykjavík: Orkustofnun: Jarðhitadeild, August 1980), 87, https://orkustofnun.is/gogn/Skyrslur/1980/OS-80026-JHD15.pdf.



Green Hydrogen

National Context

> *"It is the Government's policy to promote increased utilisation of renewable energy resources in harmony with the environment. One possible approach towards this goal is production of environmentally friendly fuels for powering vehicles and fishing vessels. Hydrogen is an example of such a fuel."*[57]

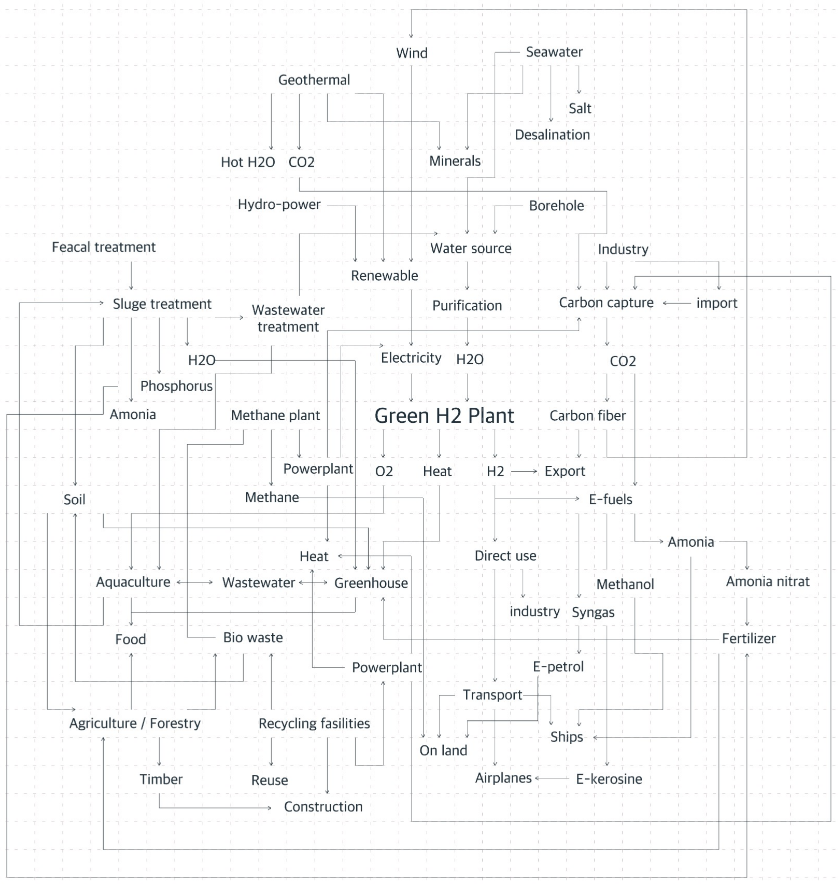
This is part of a statement made by the Minister of Environmental Affairs, Halldór Ásgrímsson in February 1999 when The Hydrogen and Fuel Cell Company (now named Icelandic New Energy (INE)) was founded.[58] The company was formed as a public private partnership following a declaration from the Government of Iceland declaring that Iceland would like to explore the possibility of exchanging from a fossil fuel paradigm in transport to utilizing hydrogen. INE is a research and demonstration company focused on hydrogen technology. INE has taken part and operated numerous projects and it is worth mentioning that INE operated a research and development project testing fuel cell buses and a commercial hydrogen refueling station in 2001. INE has taken part in testing passenger vehicles and hydrogen and fuel cells in marine applications. INE is now participating in research, development and demonstration projects related to hydrogen, methane, batteries, bio-diesel, etc. both for land and marine applications.

There is a long list of companies, groups and people, both Icelandic and foreign stakeholders and investors, as well as all kinds of partnerships and entrepreneurship that are, or have been developing and researching the utilization of 'green hydrogen' in Iceland in recent years. In this research it is not relevant to discuss each and everyone since this is rapidly changing and a **vibrant field**.

Unlike when Bragi Árnason and his colleagues were exploring possibilities of the 'hydrogen economy' in the late 70´s I think we are facing different circumstances in many ways today. Technological innovations, public interest, regulatory bodies and world politics could finally give rise to 'green hydrogen' on the industrial scale where it is most needed to lower world CO2 emissions.
So I ask, where is the appropriate place for such a space and energy demanding business?

57 Bragi Árnason and Thorsteinn I Sigfússon, 'Iceland – a Future Hydrogen Economy', International Journal of Hydrogen Energy 25, no. 5 (1 May 2000): 394, https://doi.org/10.1016/S0360-3199(99)00077-4.

58 Árnason and Sigfússon, 394.



Green Hydrogen

Eco-Industrial parks

If such a large scale industrial element is introduced with a function with few if any pre-exemples in Iceland the first that comes to mind is an area that has a room for maneuver. It could fit in a site that is in some kind of development, either a new industrial site or where a site is being redeveloped. As a part of Iceland's Climate Action Plan is the implementation of the circular economy. Eco-industrial parks will play a fundamental role in that. "Eco-industrial parks (EIP) are an organization of businesses grouped around material needs and outputs, [...]in the form of one entity using the by-product of another entity as input.[59] Recently, strategic planning has been done by the government around the ideology of "eco industrial parks" ("grænir iðngarðar").[60] Hydrogen production plant could be a **cornerstone** in such a complex.[61]

There are a few places that could fit for such an industry and now there are a few hydrogen and alternative fuel projects being considered. I think it is important to mention a few of them by company and places such as; Landsvirkjun at Ljósafossvirkjun, Vetnis and Hydrogen Ventures Limited in Reykjanes Geopark, Iðunn H2 in Helguvík, Qair Iceland at Grundartangi and hydrogen production as a part of conceptual design of a port in Finnafjörður.

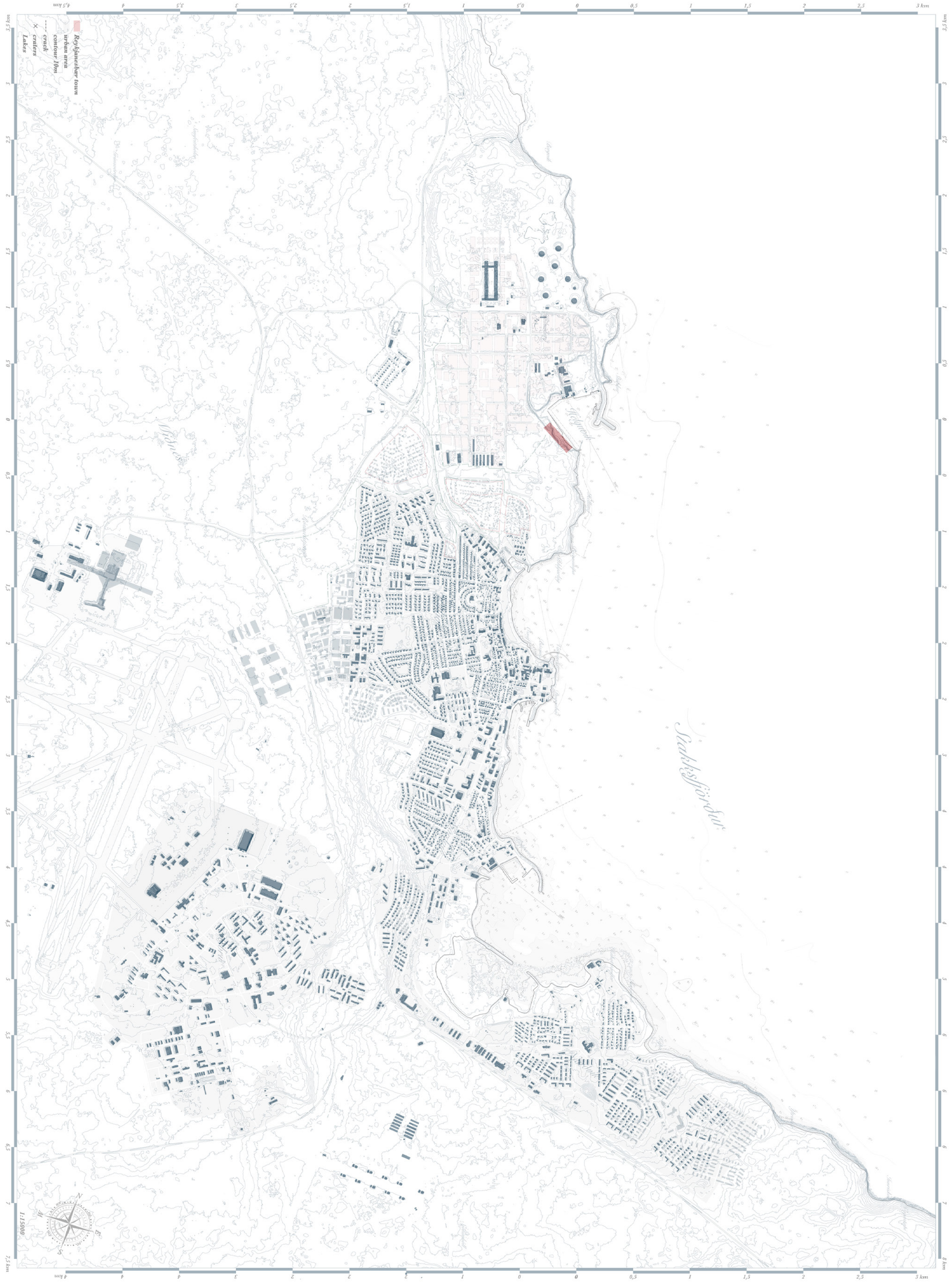
59 Daniel V. Perrucci et al., 'A Review of International Eco-Industrial Parks for Implementation Success in the United States', City and Environment Interactions 16 (1 December 2022): 1, https://doi.org/10.1016/j.cacint.2022.100086.

60 Deloitte et al., 'Grænir Iðngarðar' (Íslandsstofa, Norðurþing, Landsvirkjun, Atvinnu-og nýsköpunarráðuneytið, September 2021), 11.

61 Deloitte et al., 83,183,186,189.

5
Conclusion

Location



Conclusion

Now I have identified the fundamental nature of the energy transition with the focus on utilization of green hydrogen. It seems relevant to take hydrogen production in Iceland to the industrial scale. There is a growing public and political interest in the field and a call for action in energy transition both nationally and internationally. There is a growing demand for green hydrogen. In the global context there is a growing need for green hydrogen in the chemical and energy demanding industries as well as a supplement in domestic gas networks, specially in Europe following the disruption of the Russian invasion. In the national context it would have the most impact on CO2 emissions to focus and invest on direct usage of hydrogen in the marine and aviation sector, otherwise hydrogen based E-fuels as a second choice. Such a production could be thought of as a reasonable extension of the public energy network of Iceland. IEA states that the near-term opportunities for real-world actions lie in making the most of "existing industrial ports to turn them into hubs for lower-cost, lower-carbon hydrogen."[62]

62 International Energy Agency, 'The Future of Hydrogen', 16.

Location

My design project takes place in **Helguvík** and here are the main reasons that make this particular place interesting for an architecture student to work with:

Helguvík is adjacent to a town, the Helguvík harbor is within 800m from the nearest residential houses of Reykjanesbær. Because Helguvík is in a walking distance from a residential area any development that takes place there has to work carefully with physical and social barriers and connections that often are challenging between big industries and local residents.

It is within 3 km from the only international airport, Keflavík airport where Helguvík serves mainly now as an oil import hub for the airport and the two places are connected with an oil pipe.

Short distance from existing marine trafic.

35 km from the capital center. Roughly **70%** of the total population of Iceland lives within a **35 km** radius which makes short access to labor force.

The place is clearly visible from land, air and sea.

In Helguvík is an industrial port and infrastructure that is not currently operating to its full potential. That gives the place an advantage to export and serve as a fuel hub for nearby cargo and fishing vessels.

Helguvík and the surrounding industrial area is in the state of rebirth towards greener industry. There has been a controversy around old-minded industrial development in Helguvík and locals.

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