FRAUNHOFER INSTITUTE FOR ENERGY ECONOMICS AND ENERGY SYSTEM TECHNOLOGY, IEE

STUDY ON THE PRODUCTION OF GREEN HYDROGEN IN THE RIO NEGRO PROVINCE

Report

STUDY ON THE PRODUCTION OF GREEN HYDROGEN IN RIO NEGRO PROVINCE

CONFIDENTIAL

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Executive summary

In recent years hydrogen has globally been identified as a key enabler of the future clean energy mix. Many regional, national and international hydrogen strategies and roadmaps have been published. They share the vision, that in the long term carbon neutral and in particular green hydrogen produced via water electrolysis using green electricity can account for a significant share of around 20% of the final energy demand and as feedstock for many industrial applications. The main potential for hydrogen is expected in hard-to-decarbonise energy uses such energy-intensive industries, heavy duty vehicles, aviation, shipping and heating applications. In consequence, hydrogen produced through renewable-powered electrolysis is expected to grow dramatically in the coming years with significant production capacities and rapidly decreasing cost towards 2030 already. Due to the synergies between green hydrogen and renewable energy, the market growth of renewable electricity in particular solar and wind energy is expected to accelerate while reducing generation cost.

Hydrogen is expected to become a global trade commodity supporting enhanced climate ambitions to achieve a "deep decarbonization". According to Bloomberg New Energy Finance (BloombergNEF), many large economies in Asia such as China, Japan, the Republic of Korea and most European countries are expected to have limited renewable power generation capacities. I.e. in order to meet the long-term EU hydrogen demand of around 2250 TWh/a, recent studies confirm, that at least 1000 TWh/a of hydrogen will have to be imported to Europe - at cost of just under 5 $/kg if favorable land-based PV and wind sources are considered.

At global level, hydrogen generation based on solar and wind power plants will ultimately be implemented in these most favorable regions. These must be brought into line with the demand for energy, fuels and basic chemicals in the corresponding industrial regions. Hydrogen can be transported directly in liquid form in analogy to LNG (Liquefied Natural Gas) and in chemically bound form such as ammonia, methanol or LOHC (Liquid Organic Hydrogen Carriers). Many regions in the world are preparing for this form of trading of sustainably produced energy carriers and basic chemicals, which enables to develop new energy and hydrogen related partnerships beyond the previous fossil energy partnerships. The Government of the Rio Negro province has identified these opportunities and is aiming to become a frontrunner for the "green hydrogen economy" in Argentina and South America by positioning the region at an early stage of the technology innovation and market implementation of hydrogen production and utilization.

The focus of this study is on analyzing different locations in the Rio Negro province for the production of green electricity from wind and solar as well as identifying suitable hydrogen production sites as well as the corresponding infrastructure for domestic applications as well as for export scenarios. For the domestic application a project scale of 100 MW electrolyser capacity has been chosen – in line with other international initiatives. This scale is sufficient to show significant economy of scales effects and put the province on the international landscape of green hydrogen projects.

For the implementation of a first electrolyser system with 100 MW in 2025 as in the "domestic scenario", the cost optimum of the configurations analysed here will be achieved if the electrolyser is located in El Chocón and the consumer is in Plaza Huincul or Cipolletti. For this case, hydrogen production cost are below 4 US$/kg. But also for the other electrolyser locations investigated, scenario-combinations can be found in which costs are below 4.5 US$/kg.

In order to achieve competitiveness, the establishment of a domestic hydrogen market, the implementation of the required market and technical regulations as well as creating public awareness and acceptance have to be considered key enabling policies. Another important aspect of capacity building is international collaboration in research and development and the public support for the implementation of pilot and demonstration projects in an early phase.

Currently, Argentina possess a local grey hydrogen market (hydrogen produced by steam reforming of methane), where 328 kt/a of hydrogen are being consumed mainly in the petrochemical (85%), chemical (8%) and refining (7%) industries. Therefore, transition from grey hydrogen towards a green hydrogen economy should beside the transport sector where the highest hydrogen revenues can be achieved, also consider these industries. However, the economics of green hydrogen require market incentives in order to create a business case for the industries involved. Establishing such policy instruments would accelerate the capacity building and commercial experience in green hydrogen production, the development of a local supply chain and thereby increase the potential share of the value chain in the country. For the implementation of the 100 MW electrolyser scheme, the investment costs are approximately 280 to 300 million US$ including electricity generation and transport. For the implementation of a 500 MW electrolyser in 2030 as in the export scenario, the total investment costs amount to at least 1.8 to 2 billion US$.

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Introduction

In order to meet the global challenge of limiting global warming to below 2 ° C, the share of fossil fuels in global energy systems must be reduced to a minimum. Instead of fossil fuels, a sustainable circular energy economy must therefore be installed, which will - to a significant extent - be based on hydrogen. In addition, large quantities of hydrocarbons will continue to appear in some sectors in the future, but these will then be produced with the help of renewable energies and greenhouse gas-neutral hydrogen and carbon. In this respect, energy systems and industries cannot be "decarbonized", but must achieve greenhouse gas neutrality.
In Argentina, this process was initiated in 2006 with the enactment of Act 26.190 that among other things, declared of national interests the generation of renewal energy in Argentina. Such Law was then modified by Law 27.191 which was implemented in 2016 by the RenovAr program of the National government with increasing renewable energy installations in the country up to almost 3GW. This has led to a share of renewable energies in the electricity mix of around 8% today.
However, it is now becoming increasingly clear that hydrogen and its other synthesis products will play a central role in ensuring that all energy-consuming sectors such as transport, industry and buildings are greenhouse gas-neutral. In addition to its direct use in various areas of application, hydrogen is also becoming increasingly important for the system integration of renewable energies due to its flexibility in the production, the possibility of storage and its transportability at large scales.

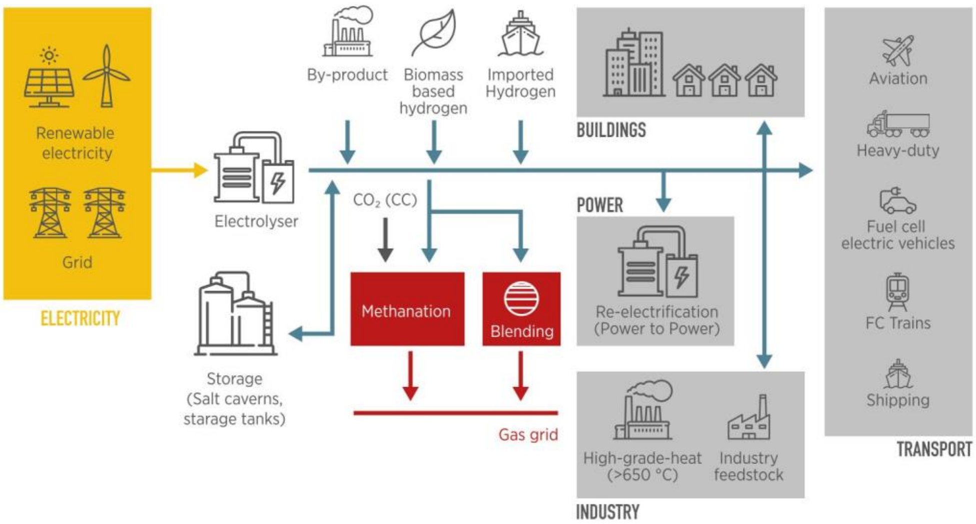

Figure 1: Integration of hydrogen in the future energy systems (International Renewable Energy Agency (IRENA) 2018)

As the production of electricity from renewables increases, so will the economic use of energy storage and transportation. Water electrolysis will thereby become an important industrial policy component, on the one hand for the production of the required hydrogen, on the other hand as a flexibility option in the future power grid with a high share of renewable energies. In the medium to long term, hydrogen will play an important role in the National energy transition and the international export market.
At global level, hydrogen generation based on solar and wind power plants will ultimately be implemented in the most favorable regions. These must be brought into line with the demand for energy, fuels and basic chemicals in the corresponding industrial regions. Hydrogen can be transported directly in liquid form in analogy to LNG (Liquefied Natural Gas) and in chemically bound form such as ammonia, methanol or LOHC (Liquid Organic Hydrogen Carriers). Many regions in the world are preparing

for this form of trading of sustainably produced energy carriers and basic chemicals, which enables to develop new energy and hydrogen related partnerships beyond the previous fossil energy partnerships. The international ports and their adjacent industrial regions are of great importance for the realization of such trade routes, as not only refineries are often located here, but a distribution infrastructure for hydrogen products is also provided via the logistics routes.

Much of the renewable energy resource such as solar and wind is located far from population centers and produce electricity only part of the time. Hydrogen has been identified as the perfect carrier for this energy. It can store the energy and distribute it to wherever it is needed. Hydrogen production cost is dominated by the electricity cost, with a share of approximately 50-70% of the LCOH (Levelised Cost of Hydrogen). These favor regions in the world with the best natural resources and consequently lowest Levelised Costs of Energy (LCOE) from renewable energies, such as wind energy in Patagonia.

The Government of the Rio Negro province has identified these opportunities and is aiming to become a frontrunner for the "green hydrogen economy" in Argentina and South America by positioning the region at an early stage of the technology innovation and market implementation of hydrogen production and utilization.

3 Description of technical background and hydrogen market

3.1 Technologies for hydrogen production by electrolysis

In principle, several methods can be used to generate hydrogen by electrolysis. Alkaline water electrolysis (AEL) with liquid potassium hydroxide and acidic membrane or PEM electrolysis (PEM: Proton Exchange Membrane) work at low temperatures between 50 and 80 ° C. The high temperature or steam electrolysis uses a solid oxide electrolyte made of ceramic materials and is operated at approx. 800 ° C.
Alkaline electrolysis has been a process that has been used industrially since the end of the century before last and in the 20th century already achieved good levels of efficiency and long service life in stationary continuous operation.

Alkaline electrolysis, as a technology that has been technically mature and commercially advanced for many decades, represents the world's largest electrolysers. The largest is located at the Aswan dam in Egypt and has an electrical power of 156 MW and was built by BBC/DEM AG to supply a fertilizer plan (Smolinka et al. 2011) (Hydrotechnik 2021). The largest pressurized electrolyser is in Peru and has an electrical power of 22 MW and was manufactured by LURGI (Smolinka et al. 2011). Due to its well-developed technology, further improvements are expected mainly in increased lifetime and cost reductions through scaling effects and mass production.

During 2019 Q1, there have been announcements to install new systems of up to 100 MW per installation. The company H2V Industry plans the first two 100 MW plants with AEL from the company Hydrogen pro to produce CO2 free hydrogen in large quantities. The plants will be built near Le Havre and Dunkerque in France. The first plant is to be delivered by the end of 2021. Further 100 MW plants are to follow (Sampson 2018) (Sampson 2019).

In the "element one" project, the companies Gasunie, TenneT and Thyssengas are planning a 100 MW electrolyser, which will be connected to the grid step by step from 2022 onwards. Electricity and gas infrastructures are to be linked at the plant location in Germany (Element 2019). Amprion and Open Grid Europe (OGE) are also planning a 100 MW plant in the "hybridge" project, which will go into operation in Germany in 2023. In addition, a hydrogen infrastructure is to be built using a hydrogen network (Amprion GmbH und Open Grid Europe GmbH 2019).

PEM electrolysis (TRL 6-8) has been used successfully in niche applications for around two decades. In the last ten years it has undergone significant further development for applications in the future energy market, as the technology is particularly suitable for coupling with renewable energy sources, due to its compact design, good suitability for operation at high pressure, high dynamics allowing for rapid load changes, etc.
PEM electrolysers have a comparatively large wide load range. They can be operated in the range of 0-100% and also tolerate short-term operating conditions in overload. PEMEL is characterised by its compactness and efficiency. It can follow fast load gradients. Forecasts for cost reductions of PEMEL are significantly higher than cost reductions for AEL systems, because in addition to extended lifetime and scaling effects, efficiency increases and cost reductions through new materials are expected.

PEMEL is at the beginning of industrial implementation. The largest PEMEL is to be implemented in the "Refhyne" project by Shell and ITM Power at the Shell Rheinland refinery in Germany. The hydrogen is to be used primarily for the treatment of products in the refinery. The technology is also being tested for possible uses in other sectors. The plant with a capacity of 10 MW is currently under construction. (Shell 2018)

Basically, the current hydrogen electrolyser market is segmented into AEL and PEM which differ in processing methods and other operational aspects. Their conceptual design can be observed in Figure 2, while their main characteristics are compared in Table 1.

Table 1: Main characteristics of AEL and PEM electrolysis (Source: NOW, 2018)

	ALKALINE ELECTROLYSIS (AEL)		**PROTON EXCHANGE MEMBRANE ELECTROLYSIS (PEMEL)**	
	State of the art	2030	State of the art	2030
Maximum Available Stack Sizes	68 kg/h, 3.2 MW	---	58 kg/h, 3 MW	---
Specific Energy Consumption [kWh/kg]	47.8 – 54.5	46.7 – 52.3	52.3 – 54.5	48.9 – 53.3
Life-time [h]	50,000-70,000	65,000-90,000	20,000-60,000	40.000 - 80.000 h

In addition, high temperature solid oxide electrolysis (HTEL) is currently being developed and scaled to ratings relevant to future markets.

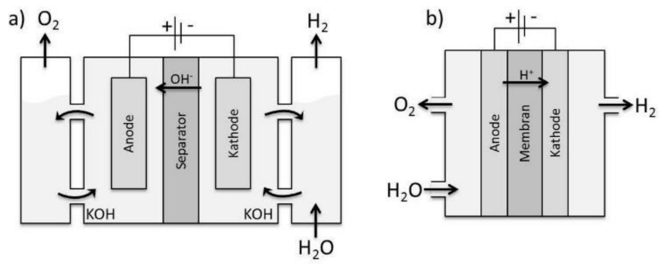

Figure 2: Conceptual set-up of two electrolysis cell technologies (a) alcaline (b) PEM (Steinmüller 2014)

The high-temperature electrolysis is at a development level of TRL 4-6, a broad field test experience is not yet available. Their decisive advantage is the very good electrical efficiency when waste heat is available on site at a temperature level of 200 ° C or higher. It is therefore particularly suitable for coupling with industrial processes. Water vapour is split instead of liquid water, which results in a significantly lower electric energy demand of only 36 kWh/kg –around 30% less than AEL and PEMEL. The HTEL runs at temperatures of 700-1.000°C. The electrolyte consists of zirconium dioxide, a heat-resistant ceramic material. HTEL offers advantages over AEL and PEMEL when thermally connected to a high-temperature process. In combination with a thermally linked methanation (combination of HTEL and catalytic methanation including use of process heat), the theoretical maximum process efficiency is 89% based on the calorific value of hydrogen, the practical maximum at 85%. The disadvantage of this technology lies in the currently still very limited lifetime of the stacks of less than 3,000 operating hours, which is due to a high material degradation. Furthermore, HTEL is not well scalable to high power. CAPEX for HTEL (2.250 €/kW) are much higher nowadays than investment costs for AEL and PEMEL. However, due to higher specific cost and limited scalability in the near and medium term, HTELs have not been considered for the realisation of the first plants and the focus is for further consideration on AEL and PEMEL. In the future, the HTEL will be interesting for hydrogen production for direct use in a Sabatier processes (methanation), methanol synthesis or Fischer Tropsch synthesis because of the heat supply from the processes for the HTEL.

In addition to these three technologies, other electrolysis processes have the potential to play a greater role in the future. Particularly noteworthy are the alkaline membrane electrolysis (TRL 4-6) and seawater electrolysis (TRL 1-3). Both approaches are currently researched and only limited efforts are visible in an industrial context in comparison to the more advanced technologies discussed above.

Although electrolysers can be scaled by either increasing the area and thereby current of a single cell and by increasing the voltage of a stack by the number of cells in series, there are limitations on the manufacturing process and the assembly and handling of the stack. In consequence, scaling up the plant size is obtained by using multi-stack configurations. It has been observed that scaling electrolysis devices has positive effects when it refers to CAPEX and OPEX, particularly with a significant cost reduction between 1 MW and 5 MW per module (Saba et al. 2018). The specific costs for electrolysis are reduced with increasing plant size. Since the cell area also rises with increasing plant size and the stack contributes to a large proportion of the costs, the cost reduction through scaling is not as large as with other technologies. Cost advantages mainly result due to balance of plant.

Water supply requirements

Water electrolysis requires cooling water, process water and water which is converted into hydrogen in the electrolysis process. Projects need to be designed to avoid conflicts of use with the agricultural and drinking water supply. In the case of seawater utilisation the necessary water treatment steps required for the electrolysis are preceded by the desalination.

The theoretical amount needed to produce one kilogram of hydrogen is 9 l_{H2O}/kg_{H2}, however, industrial electrolysers consume around 10 -12 l of deionized water per kg_{H2}. The total water demand is even higher and depends on the quality and the treatment available (Ion exchange, distillation, reverses osmosis or organic adsorption).

- $2\ H_2O$ → $2\ H_2 + O_2$
- 2 mol H_2O → 2 mol H_2 + mol O2
- 2*(2*1,00794 +15,9994) kg H_2O → 2*2*1,00794 kg H + 2*15,9994 kg O
- 8,9369 l H_2O → 1 kg H_2

Manufacturer information amounts to 20 to 40 l of water per kg H2 in total for a PEMEL which includes i.e. cooling water evaporation and wastewater. Before the initial start-up, the water treatment system must purify a considerable amount of water which is necessary for the cooling system. Water cooling is realised in towers as an open system, where the cooling water is trickled in the cooling tower and cooled by a forced air flow via evaporation. The cooling circuit supplies the rectifiers, electrolysis, purifiers and the compressors. If the water supply is limited closed cooling cycles can be used and wastewater can be recycled.

In order to achieve the required water quality in particular with regard to low water conductivity, which is crucial for the lifetime of the stack, electrolysers are equipped with deionisation systems. These reduce the water conductivity in accordance with the stack requirements to values below 2-10 µS/cm. In order to achieve this, these systems need to be supplied with clean water – typically drinking water quality is specified by the manufacturer e.g. in accordance with the WHO regulations which cover a wide range of microbial, chemical, radiological and acceptability aspects.

The technology applied for water purification is reverse osmosis (RO) and electroionization (EDI). RO provides the pre-cleaning and EDI is used for the fine cleaning. The cooling water is removed after the first reverse osmosis. The water for the electrolysis passes through the second reverse osmosis and the EDI.

For a long lifetime of the stack, it is usually recommended for almost every electrolyser to achieve Type I or II of the ASTM D1193 – 06 (2018).

3.2 Current electrolyser market and hydrogen market development

The electrolysis industry is currently dominated by chlorine-alkali electrolysis and otherwise plays no significant economic role, since global sales and thus production capacity have been less than 100 MW per year in recent years. Due to the increased interest in the economic potential of sector coupling and the identified demand for green hydrogen generated by renewable energies, the focus is increasingly shifting towards the water electrolysis industry. Several large international OEMs such as Siemens, Asahi Kasei and Thyssenkrupp develop their own products. In addition, it can be observed that financially strong investors and companies secure shares in established smaller electrolysis companies. At the moment, the global market is being stimulated primarily by a wide range of R&D programs. For example, several 100 MW electrolysis capacities are to be built in Germany over the next few years as part of the real-world laboratory initiative of the German ministry for Economy (BMWi).

The current international electrolysers market size is about 100 MW/a, with a global turnover of 100-150 Mio €/a, creating approximately 1,000 direct jobs. Currently a strong short-term market dynamic is visible with several projects in the pipeline at 5 MW, 20 MW and 100 MW single project scales. The expected short-term production capacity ramp-up towards 2 GW/a is possible, with 70% of that capacity expected to be realised in Europe. As an example, the Norwegian company NEL has announced in 2018 to ramp up their production capacity of currently 40 MW/a (25 MW/a until 2017) to 360 MW/a after 2020 due to orders from the US for up to 1 GW of electrolyser capacity. ITM Power has announced a manufacturing capacity ramp-up towards 1GW/a by 2024 (Cooley und Allen 2019).

With regard to the electrolyser supply chain aspects, there are in general not many components or production processes identified to be critical for mass production and relatively low investment requirements are necessary to scale production capacity. However, various materials are considered which, due to their supply risk, could limit the industrialization of water electrolysis (Smolinka et al. 2018a) (Smolinka et al. 2018b).

The International energy agency IEA has published a dataset that covers electrolysis projects worldwide that have been commissioned since 2000 as well as projects in planning or construction are also included. The cumulative project pipeline exceeds the 1 GW capacity in 2021 and reaches 3 GW in 2025.

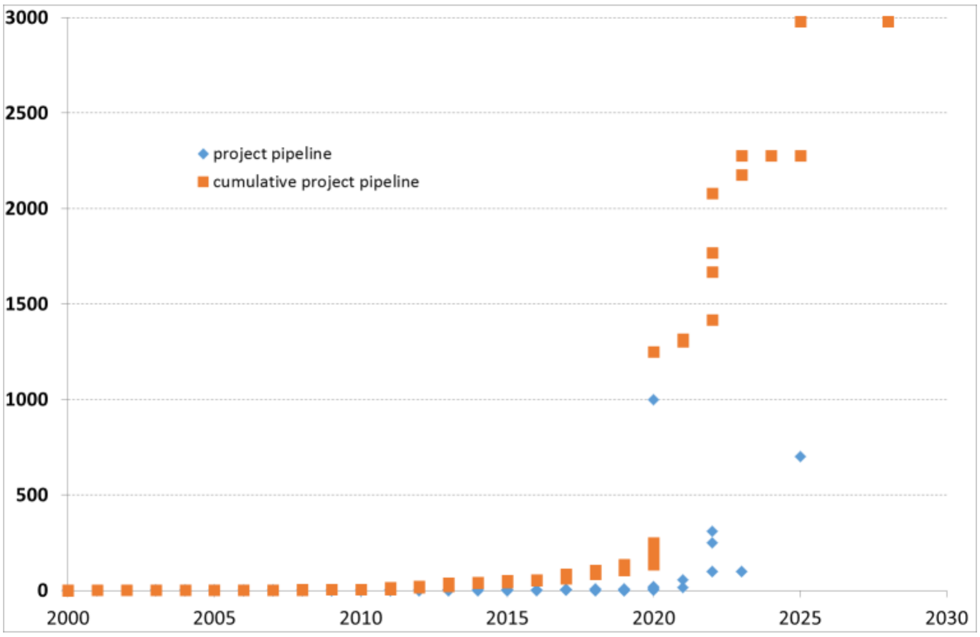

Figure 3: Current global electrolyser deployment project pipeline [MW] (International Energy Agency (IEA) 2019b)

The report "Hydrogen Insights - A perspective on hydrogen investment, market development and cost competitiveness" published in February 2021 by the Hydrogen Council assumes 90 GW of capacity deployment for electrolysis by 2030. The report states that "the industry has already announced electrolyzer capacity increases to over approximately 3 GW per year". According to their analysis, the production ramp-up scaling would translate into system costs falling faster than previously estimated, hitting USD 480-620 per kilowatt (kW) by 2025 and USD 230-380 per KW by 2030 – which represents the most ambitious cost reduction scenario published so far bit also indicates the significant advancements expected for the next decade. Their project pipeline has identified more than 200 hydrogen projects with 85% of global projects originating in Europe, Asia, and Australia.

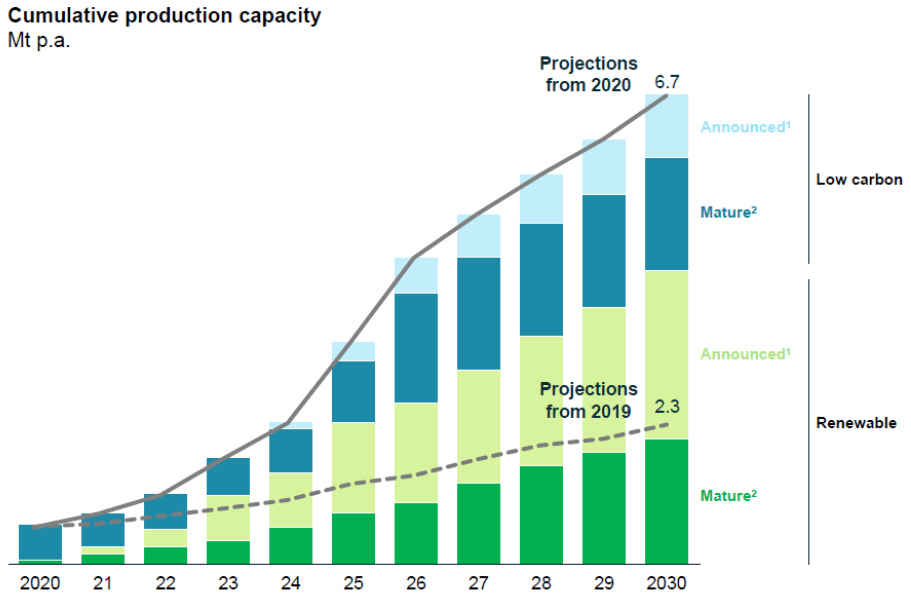

Figure 4: Expected low carbon and green hydrogen production ramp-up (Source: Hydrogen Insights, Mc Kinsey, 2/2021)

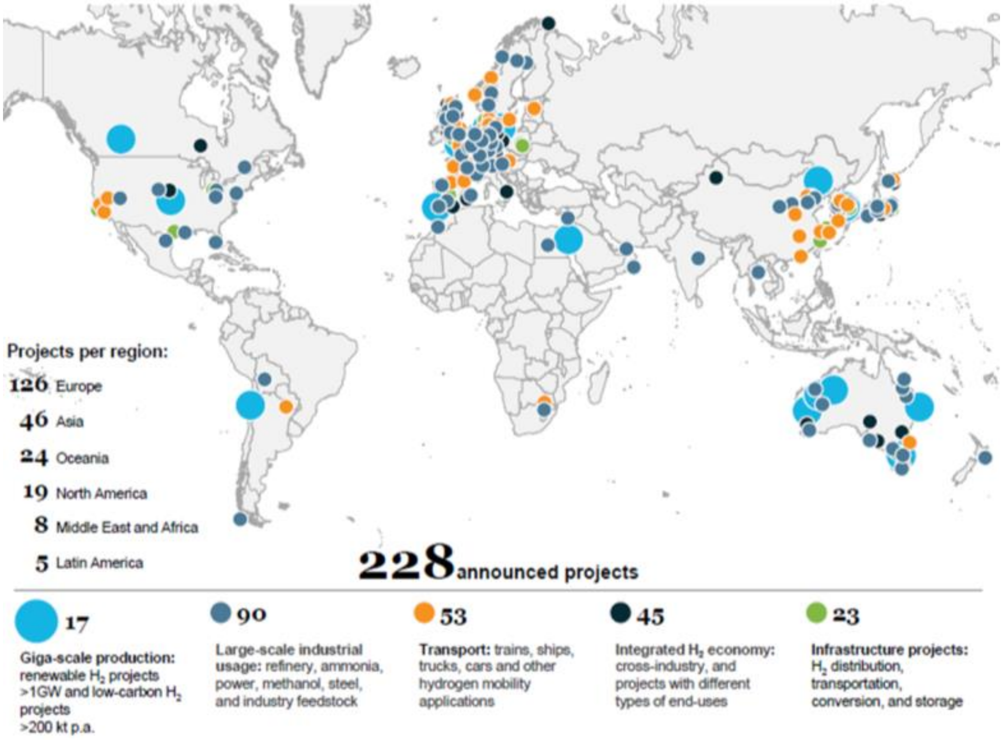

Figure 5: Announced global hydrogen projects (Source: Hydrogen Insights, Mc Kinsey, 2/2021)

3.3 Hydrogen storage, transport and distribution

Large-scale use of hydrogen as an energy carrier will require a transport and distribution infrastructure, which connects hydrogen production sites with users. If development progresses gradually from small-scale applications, transport by truck would be adequate in the early stages. In the case of large-scale application, transport by means of a pipeline infrastructure will be a critical link, as a result of factors such as the cost advantage that comes with long-term, large-scale use. Depending on the timing and the locations of producers and users, the current high-pressure natural gas infrastructure could be used for this (Melaina et al. 2013; Yoo et al. 2017; Sadler et al. 2018; Gigler und Weeda 2018).

If hydrogen is generated in a central production facility and transported to a consumer by pipeline, bulk tank or cylinder truck delivery, different transport chains are possible. The best option will depend on the amount of hydrogen being transported and the transport distance and whether the development of the infrastructure is to be successively expanded in parallel with the hydrogen usage expansion. The development of a global infrastructure must be planned for the long term and take into account not only the production country but also the recipient country.

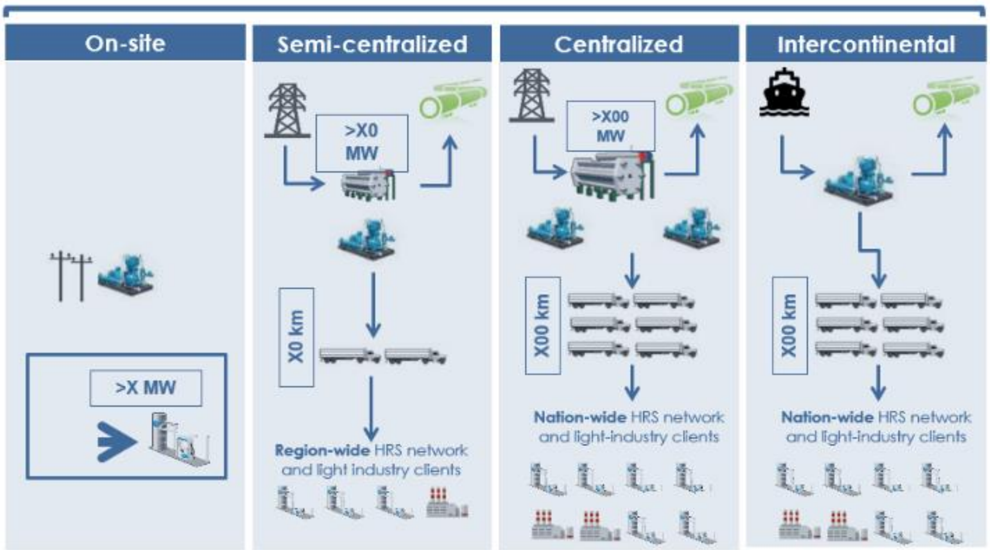

Figure 6: Potential future ramp up pattern of a hydrogen supply chain (HINICIO 2016)

Hydrogen has a high gravimetric energy density, higher than all other gases, but a low volumetric energy density. Therefore, the storage of hydrogen under atmospheric conditions is not effective. In order to reduce the costs for the storage and transport of hydrogen, the volumetric energy density must be increased and thus the volume reduced. There are several ways to store hydrogen.

Commercially available processes are compression and liquefaction. Further processes such as the binding of hydrogen in metal hydrides or the chemical binding in liquid organic hydrogen carriers (LOHC) or the use of other chemicals as hydrogen carriers such as ammonia are under development.

(Ishimoto et al. 2019) calculate the transport losses for liquid hydrogen and ammonia in their study (see Figure 7 and Figure 8). The comparison analyses the whole value chain from hydrogen production to the receiving terminal and observes the long-distance transport of hydrogen with LH2 and NH3 for regional and global markets.

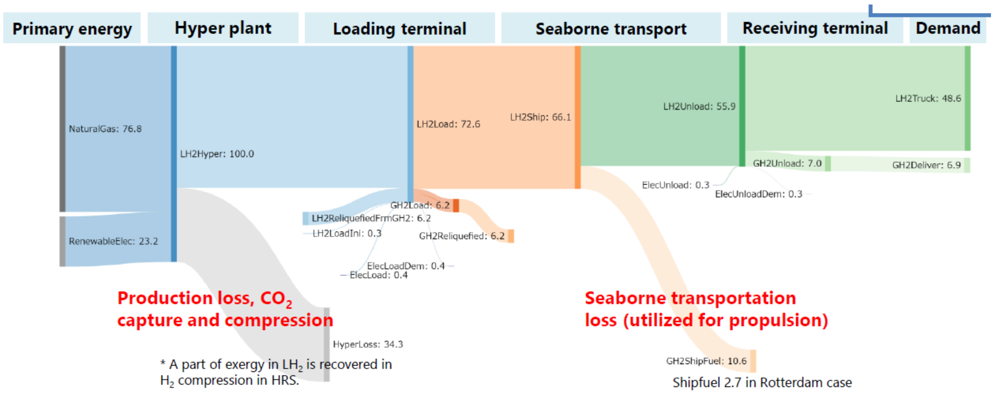

Figure 7: Energy balance of LH2chain for power plant (Ishimoto et al. 2019)

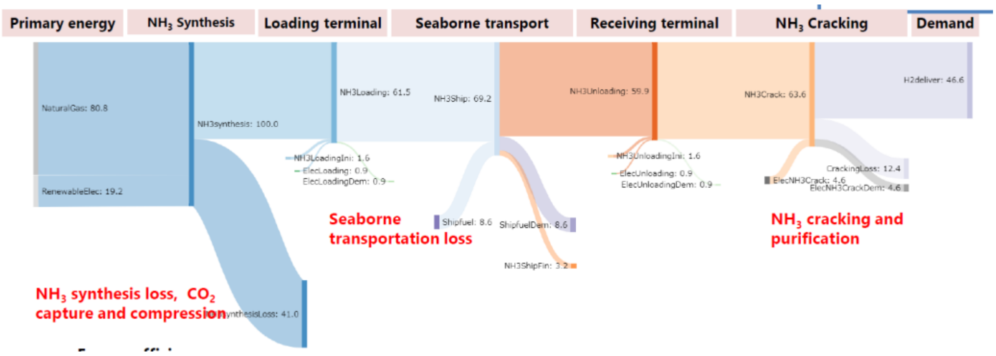

Figure 8: Energy balance of NH3chain for power plant (Ishimoto et al. 2019)

For short distance transport also ship and pipeline were compared (see Figure 9). Breakeven range seems to be around a few thousand km. Nevertheless the optimum transport technology depends on range and flexibility requirement regarding the destination of the hydrogen.

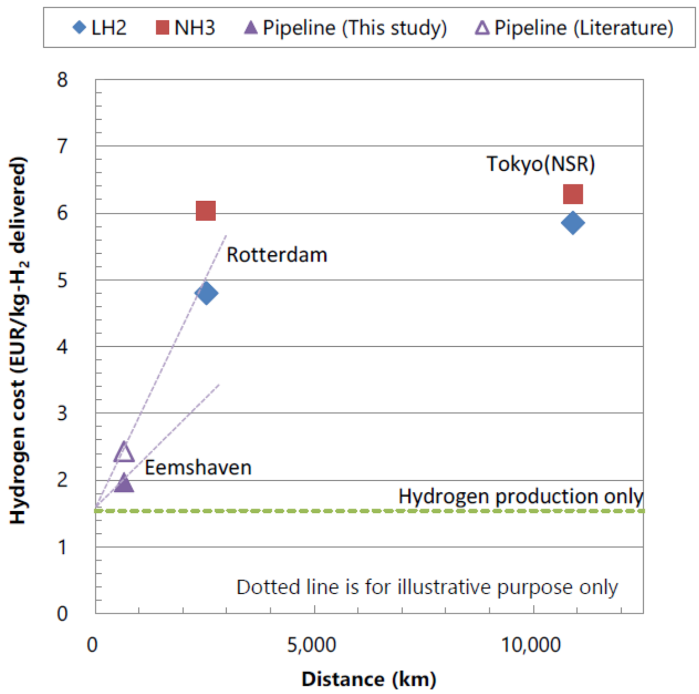

Figure 9: Breakeven range between ship and pipeline (Ishimoto et al. 2019)

For pipeline transport (Wang et al. 2020) state that 1.5-2.3% of the transported hydrogen's energy content is consumed for compression purposes for every 1,000 km of distance covered, assuming electricity-driven compressors.

3.3.1 Transportation costs for truck and pipeline transport

The costs for transport depend on the two most relevant parameters: transporting distance and the mass respectively volume flow of hydrogen. The transport costs for different options for domestic scenarios are calculated for truck and pipeline transport. Liquefaction is only used for export scenarios because of high investment costs and energy losses it is not economical for domestic use.

Results for transport costs calculation

Based on the assumptions for the project (see chapter 6.3), that the same standard pipeline diameter is used for all hydrogen quantities, the transport costs for different distances and hydrogen quantities were calculated for transport by truck and by pipeline.

The following graphic shows the transport costs in USD / kg hydrogen depending on different distances and hydrogen quantities (flow rates). In each case, only the costs for the cheaper transport option (truck or pipeline) is shown and it is marked with color which transport option is cheaper (truck = yellow, pipeline = blue).

	Distance [km]																							
Hydrogen Flow [t/a]	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600
2.000	0,29	0,38	0,45	0,54	0,61	0,61	0,70	0,77	0,86	0,93	0,93	1,05	1,10	1,18	1,26	1,34	1,34	1,42	1,50	1,58	1,65	1,65	1,74	1,81
4.000	0,29	0,38	0,42	0,50	0,58	0,61	0,70	0,77	0,82	0,89	0,93	1,02	1,10	1,14	1,21	1,30	1,34	1,42	1,50	1,53	1,62	1,65	1,74	1,81
6.000	0,21	0,36	0,43	0,49	0,56	0,61	0,70	0,75	0,83	0,88	0,93	1,02	1,07	1,15	1,20	1,29	1,34	1,42	1,47	1,54	1,61	1,65	1,74	1,79
8.000	0,16	0,32	0,42	0,50	0,56	0,61	0,67	0,76	0,82	0,88	0,93	1,02	1,08	1,14	1,21	1,27	1,34	1,40	1,47	1,53	1,59	1,65	1,74	1,80
10.000	0,12	0,26	0,38	0,49	0,55	0,61	0,69	0,75	0,81	0,87	0,93	1,02	1,08	1,14	1,21	1,27	1,34	1,40	1,46	1,53	1,59	1,65	1,74	1,80
12.000	0,11	0,21	0,32	0,42	0,53	0,61	0,69	0,75	0,82	0,88	0,93	1,01	1,07	1,14	1,20	1,27	1,34	1,40	1,47	1,53	1,61	1,65	1,73	1,79
14.000	0,09	0,18	0,27	0,36	0,45	0,54	0,63	0,72	0,81	0,88	0,93	1,01	1,08	1,14	1,20	1,26	1,34	0,18	1,46	1,53	1,59	1,65	1,73	1,79
16.000	0,07	0,16	0,23	0,32	0,39	0,48	0,55	0,63	0,71	0,78	0,87	0,94	1,03	1,10	1,19	1,26	1,34	1,40	1,47	1,53	1,59	1,65	1,73	1,80
18.000	0,07	0,13	0,21	0,28	0,36	0,42	0,49	0,56	0,63	0,70	0,77	0,85	0,91	0,98	1,05	1,12	1,19	1,26	1,34	1,40	1,47	1,54	1,62	1,68
20.000	0,06	0,12	0,18	0,26	0,32	0,38	0,44	0,50	0,56	0,63	0,70	0,76	0,82	0,88	0,94	1,01	1,07	1,14	1,20	1,26	1,32	1,39	1,45	1,52

Truck Pipeline

Figure 10: Transport costs in USD / kg hydrogen depending on different distances and hydrogen quantities (flow rates).

Transport by truck and trailer is cheaper for lower hydrogen quantities and the construction of pipelines will become more important for higher hydrogen quantities. Depending on the range of assumptions applied for this study, the hydrogen quantity for a 100 MW electrolyser plant is about 8,000 to 13,000 t/a.

It should be mentioned that the installation of a pipeline infrastructure for hydrogen transport needs a long time and that the pipelines may not be installed until 2025. Truck and trailer can then also be used as an interim solution.

The energy required for the conditioning of the hydrogen to transport it via pipeline (100bar) is 0,025 kWh_{el}/kWh_{H2}. For transporting the hydrogen through the pipeline additional 0.0509 $MWh_{el}/kWh_{H2}/km$ are necessary. (Dambeck et al. 2020a)

3.3.2 State of the art for liquid hydrogen exports

Liquid Hydrogen Storage today

Liquid gas storage refers to the storage of hydrogen in cryogenic storage tanks. The hydrogen is liquefied by cooling and compression. The boiling point of hydrogen is at -253°C under ambient pressure. The liquefaction of hydrogen for storing the gas is energy-intensive. Approximately 30% of the hydrogen energy (@LHV) is currently required for liquefaction, although processes are under development to reduce the demand to below 20%. The industry is working on energy optimized large scale hydrogen liquefaction with 100 TPD of hydrogen.

The cooled and liquefied gas is stored in special insulated, cryogenic tanks, which maintain the gas condition (-253°C) and reduce evaporation losses. Stationary tanks consist of an outer and an inner tank, high quality insulation and pressure relief valves to compensate for evaporation losses. These tanks can be transported by trailer, train, or ship if the appropriate infrastructure such as loading terminals is available. With trailers for liquefied hydrogen 3600 to 4000 kg can be transported and they have a range of approx. 4000 km so that transports over long distances are possible (Fischedick et al. 2017). Due to the larger amount of hydrogen that can be transported in liquefied form per trailer, transport in liquefied form is more economical than transport of gaseous hydrogen from a distance of approx. 120 to 150 km (Krieg 2012).

Kawasaki Heavy Industries is currently designing tank ships for intercontinental transport. Each tank ship will hold 4 tanks with a volume of 40,000 cubic meters each. A demonstration ship under construction with the new tank with high-performance insulation to minimize H_2 losses has a capacity of 1,250 cubic meters.
Liquid hydrogen pipelines are only profitable for large quantities and long-term use due to the high investment costs (Fischedick et al. 2017).

Liquid hydrogen export infrastructure

The following aspects have to be considered for a hydrogen liquefaction in the vicinity of a suitable port for international export

- Hydrogen produced remotely and delivered by compressed road/rail tanker or dedicated pipeline;
- Liquefaction at port requiring good electricity network capacity and connection, land at port for liquefaction plant with adequate perimeter barrier/exclusion zone, and hydrogen tanker / pipeline receival area;
- Cryogenic storage at port;
- Cryogenic pipe transfer to ship;
- Ship berth pocket and channel of at least 14 m;
- Moderate shipping days to export market.

Table 2: Key figures for a LH2 export port Source: (Arup Australia Pty Ltd 2019)

CHANNEL & BERTH SPECIFICATION	REQUIREMENT (MINIMUM)
Channel depth	14.2m
Depth alongside	15.7m
DWT	80,000 tonnes
Berth pocket size	350m x 90m
LOA	300m

Hydrogen Port Facilities Cost

Dedicated port facilities are needed to import and export liquid hydrogen by ship and transport the hydrogen to the hinterland of these ports. Port facilities include, amongst others, liquid hydrogen terminals, liquid hydrogen storage tanks, liquid hydrogen truck loading, evaporation units, Liquid Organic Hydrogen Carrier (LOHC) terminals, storage tanks, dehydrogenation plants, ammonia terminals, storage tanks, ammonia cracking installations, etc.

The estimated investments that need develop the port infrastructures are:

- Liquid hydrogen terminal and storage, CAPEX about 1 billion Euro
- Ammonia terminal, storage and ammonia cracking installation, CAPEX about 300 MEuro
- LOHC terminal, storage and dehydrogenation plant,
  CAPEX – especially dehydrogenation - plant 200 MEuro
- Port pipeline infrastructure for hydrogen, ammonia, bunkering facilities and multi modal logistic centres, CAPEX 1 billion Euro.

In total an investment of about 2,5 billion Euro in port facilities is needed. An estimated total of 8 ports in Europe needs to realize these port facilities, which is a total investment of 20 billion Euro. (Hydrogen Europe 2020)

3.3.3 Train transport

The transport of hydrogen by train is another option for domestic hydrogen consumption scenarios. If the current EU development of CO2 taxation for emissions caused by conventional Diesel trucks is taken into account, transport by rail can achieve competitive costs in the near future. A study analysed by IEE with regard to train transport (Milella et al. 2020) has the aim of determining which technologies are available and suitable for hydrogen transport, to review regulatory requirements and to examine the economic viability in comparison with existing road transport. Numerous boundary conditions and technical as well as regulatory constraints including i.e. intermodality of transport modes such as the use of the same storage tank on road and rail, as well as international approval and the adaptation of current standards, are currently limiting the choice with regard to this kind of hydrogen transport.

Train transport was not taken into account in the cost analysis for this study, because several aspects would have to be considered and transferring the results of the study for Germany to Argentina is complex due to different boundary conditions:

- Technical, logistical and regulatory requirements
- construction and licensing requirements
- Restrictions on the part of the railroad infrastructure
- Restrictions on the departure and arrival times

Calculation of train transport feasibility and costs should be taken into account in a next step as soon as more concrete plant configurations, sites for electrolysis and hydrogen consumers have been determined.

3.4 Hydrogen applications

Hydrogen is very versatile and can be used in multiple ways. These multiple uses trigger the development of different markets and can be grouped in two categories:

- **Hydrogen as a feedstock (material-based uses)**: consumption of hydrogen as a fundamental building block for the manufacture of ammonia, and hence fertilizers, and of methanol, used in the manufacture of many polymers. This is a role whose importance is being recognized for decades and will continue to grow and evolve.
- **Hydrogen as an energy vector enabling the energy transition**: The usage of hydrogen in this context has started already and is gradually increasing. In the coming years this field will grow dramatically. The versatility of hydrogen and its multiple utilization is why hydrogen can contribute to decarbonize existing economies.

Hydrogen applications may be grouped in the following five categories (see Figure 11):

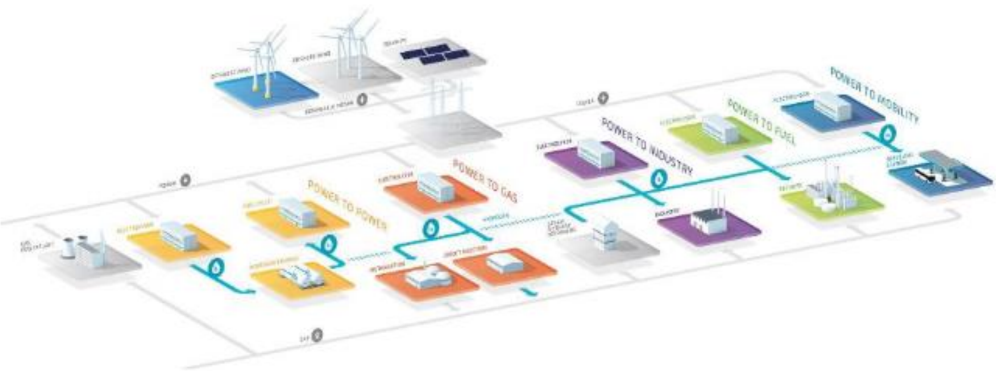

Figure 11: Destination of green hydrogen (Thomas 2019)

3.5 Hydrogen market development

The hydrogen market is established worldwide. According to IEA in 2017, the current hydrogen market has a total value of 115 billion USD and a significant growth is expected for the coming years up to 155 billion USD by 2022. The hydrogen market includes two segments: one where hydrogen is produced centrally and transported to consumers by pipeline, bulk tank, or cylinder truck delivery and the other one, where hydrogen is produced captive by the consumers for his own demand (Valladares 2017).

The annual demand worldwide for pure hydrogen is about 70 Mio tons and rises continuously since 1975, see Figure 12. The main consumers are refineries and ammonium production industry. Additionally, about 45 Mio tons per year of hydrogen are used in industry without prior separation from other gases (International Energy Agency (IEA) 2019b)

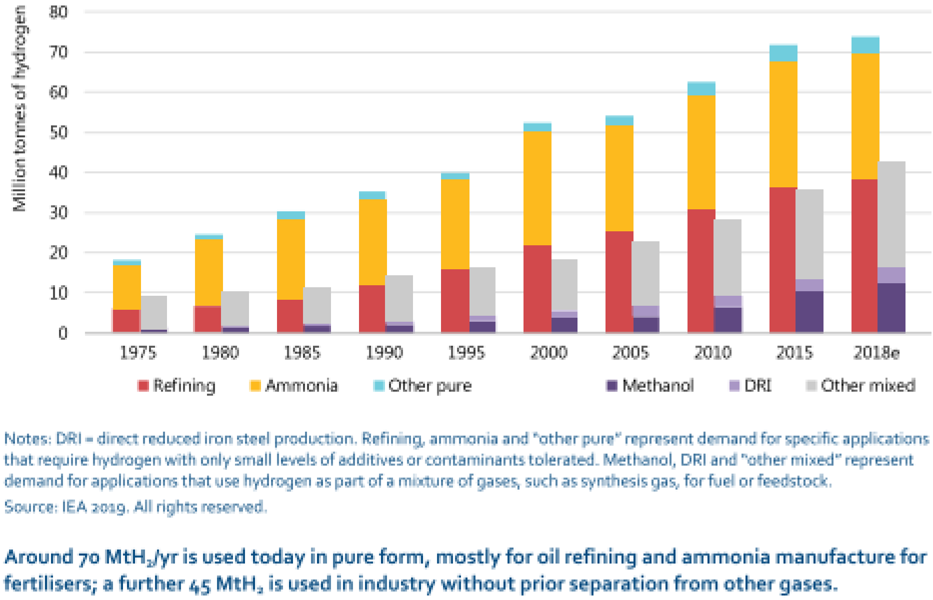

Figure 12: Global annual demand for hydrogen since 1975 (International Energy Agency (IEA) 2019b)

The hydrogen comes from various sources. Currently, 96 % comes from fossil sources such as natural gas, oil and coal, see Figure 13. The most common way of producing hydrogen is the steam reforming of methane with 48%. So far, only 4% of the hydrogen is produced by electrolysis.

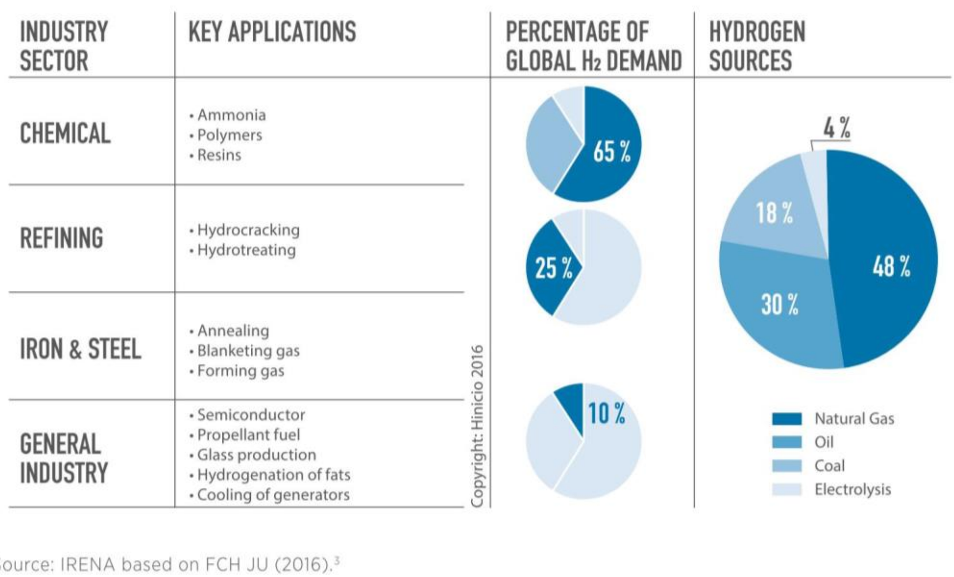

Figure 13: Global hydrogen demand and production sources (International Renewable Energy Agency (IRENA) 2018)

Various studies have identified the future global hydrogen demand. The results are summarised in Table 2. The studies show a wide range for the future demand for hydrogen between 800 TWh and beyond 20,000 TWh in 2050 and a demand up to 4,000 TWh in 2030. Most predictions do not differentiate hydrogen demand by sector.

A breakdown of demand by sector can be found in Frontier Economics 2018 and Hydrogen Council 2017.

Table 3: Range of global demand scenarios for green hydrogen in 2050 in TWh @LHV

GREEN HYDROGEN DEMAND [TWh]			
Source	2030	2040	2050
Frontier Economics 2018	-	20,000	-
Hydrogen Council 2017	3,889	7,778	21,667
IRENA 2018	-	-	2,139
IRENA 2019	833	2,222	5,278
Brinner et al. 2018	227 – 1,113	343 – 2,395	810 – 5,150
Shell Sky scenario	119	605	2,428

According to the Frontier Economics 2018 analysis there is a demand for green synthetic fuels (hydrogen produced by electrolysis with renewable energies) of 10,000 to 20,000 TWh per year in 2050 and beyond expected. It is assumed, that 25% of the hydrogen is used for second-stage processes.

The following Figure 14shows the global PtX demand estimation by sector for 2040 where it is expected that the transport sectors aviation and marine will cover over 70% respectively 50% of the energy demand by synthetic fuels. The figure also shows the forecasted PtX demand differentiated per regions.

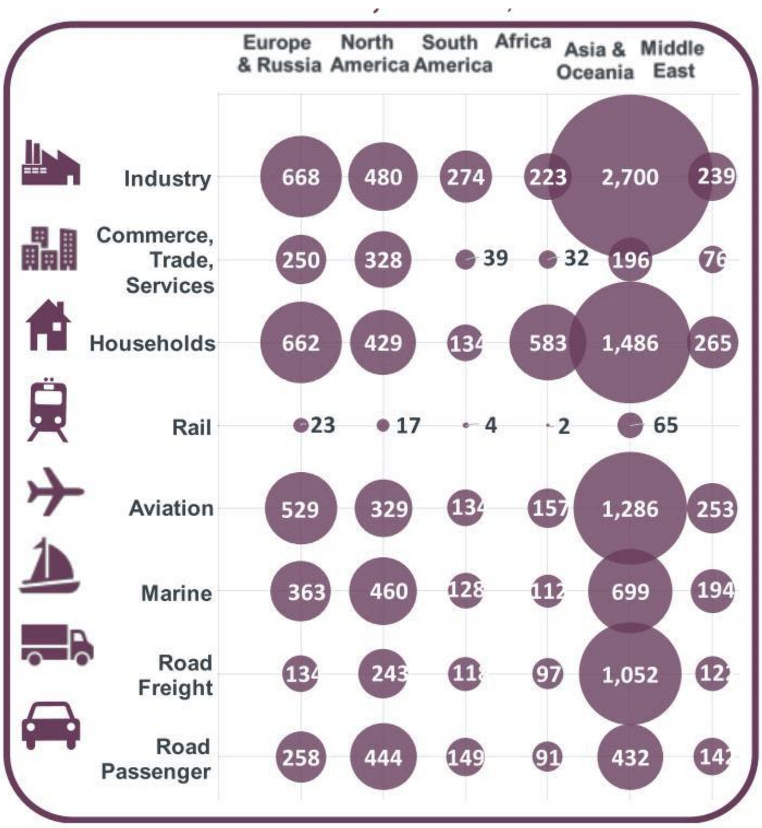

Figure 14: Global PtX demand estimation by region and sector for 2040 in TWh (Perner und Bothe 2018)

Even more optimistic is the projection of the Hydrogen Council made in 2017. They estimated that hydrogen will cover 18% of the final energy demand in 2050 and thus the global hydrogen demand rises up to 78 EJ (including 19 EJ feedstock uses) what equals 21,667 TWh (see Figure 15) which is about 10 times as high as today. Again, the transport sector is the main consumer (28%).

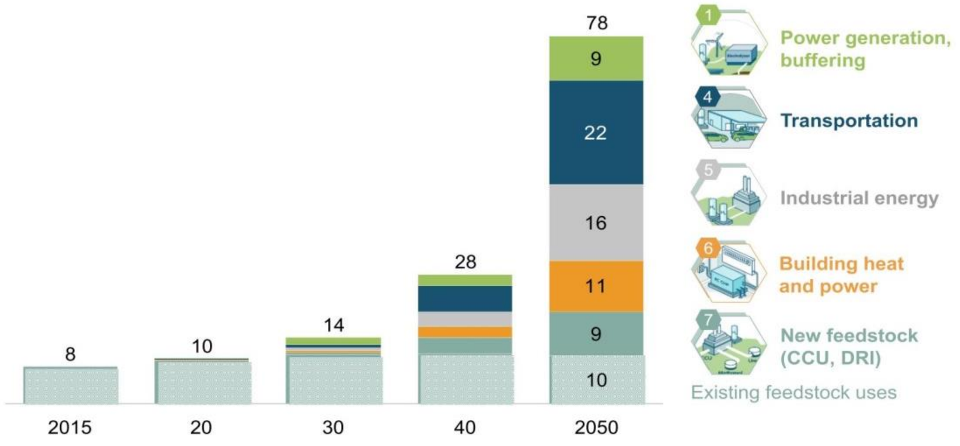

Figure 15: Hydrogen demand could increase tenfold by 2050 Hydrogen demand could increase 10-fold by 2050 (Global energy demand supplied with hydrogen, EJ) (Hydrogen Council 2017)

According to IRENA 2019, 3 EJ (= 833 TWh) of hydrogen and other transport fuels will be produced in 2030 and 19 EJ (= 5,278 TWh) in 2050.

According to Brinner et al. 2018, the global market potential of green hydrogen is up to 1,113 TWh in 2030 and 5,150 TWh in 2050, depending on the scenarios. The numbers are based on the results of different studies for 80 and 95% CO2 reduction in Germany and were extrapolated to the global demand (factor 10 in conservative scenario and factor 25 in the maximum scenario). The amounts include the substitutable hydrogen and the hydrogen demand for downstream PtX applications (e.g. Power to Methane, Power to Liquid).

According to the Shell Sky Scenarios, hydrogen emerges as a material energy carrier after 2040, primarily for industry and transport. Thus, in 2030 and 2050 the total hydrogen demand is rather small compared to other studies. The demand will increase until 2100 up to 69 EJ (around 19,114 TWh). This covers about 10% of the global energy consumption. The transport sector share of hydrogen is estimated at around 25% and at around 10 % for the industrial energy demand.

The previously described numbers show that there are some uncertainties about the size of the future hydrogen market. The quantities depend on the selected boundary conditions and assumptions for the future scenarios, e.g. biomass use. In contrast to wind and PV, biomass is, e.g. in the form of bio methane, a flexible energy carrier that can be used in competition with hydrogen for the supply of electricity and heat as well as for mobility use. This reduces the demand for hydrogen in scenarios with a high share of biomass in the future energy supply.

In the Frontier Economics 2018 study, Argentina is listed as one of the strongest potential PtX producers worldwide. An important factor in becoming a global hydrogen exporter is the potential for renewable energy, which will result in low electricity production costs and high full load hours in the PtX processes. Argentina has been identified to have one the most relevant renewable energy resources worldwide.

In this context, the recently announced EU-Mercosur trade agreement might become an important enabler.

In order to develop and build the required future infrastructure for hydrogen production as well as hydrogen storage and transport chain, the creation of demand and markets for the products is necessary. Besides, the additional value of hydrogen as a CO2-free energy source has also to be recognized in monetary terms. This can be achieved through regulatory measures and financial incentives. The number of countries with polices that directly support investment in hydrogen technologies is increasing. Most targets focus on transport. Figure 16 shows the current policy support for hydrogen deployment for different sectors and the number of countries with corresponding targets (International Energy Agency (IEA) 2019b).

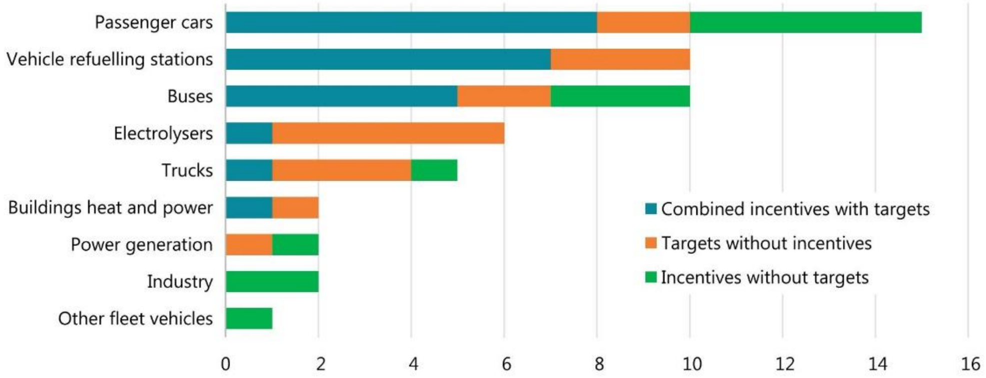

Figure 16: Policies directly supporting hydrogen deployment by target application (International Energy Agency (IEA) 2019b)

4
Initial situation and prerequisites for hydrogen production in Rio Negro

The purpose of this chapter is to describe the Rio Negro region in the context of the hydrogen economy, to analyse the availability of required resources and to identify locational advantages.

The following subsections contain information on the availability of renewable energy, water, electricity transport capacity, hydrogen transport options, ports for the potential export of hydrogen and the three potential sites for a first electrolysis plant in the province of Rio Negro.

4.1
Renewable Resources

Characteristic for the Argentinean part of Patagonia is the perpetual strong wind.

Figure 17 shows the average wind speed and the solar irradiation of Argentina. An average wind speed of 8 to 12 m/s is among the highest in the world. Solar irradiation is average, but can lead to a more balanced energy production by supplementing wind energy over time.

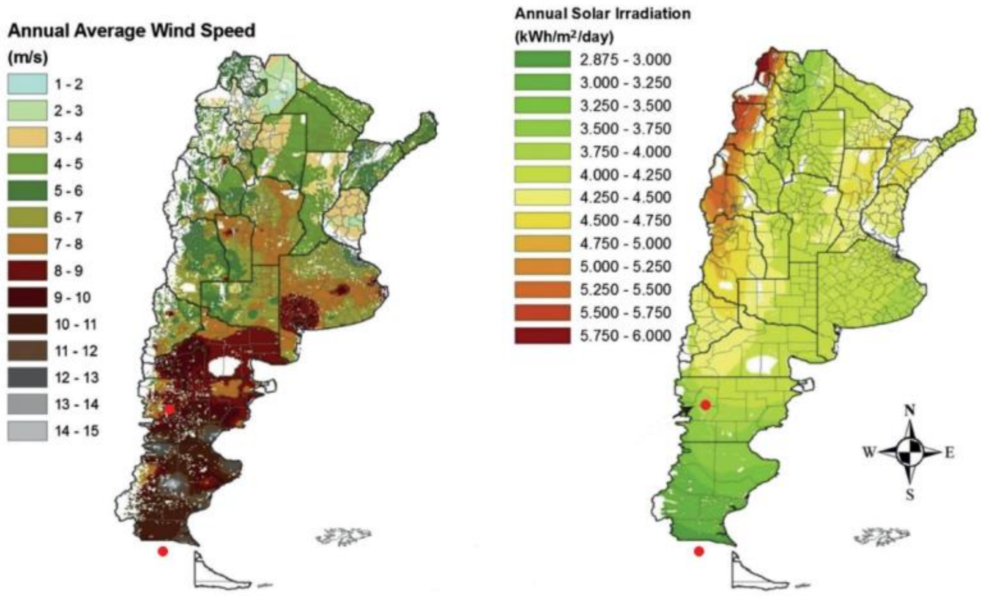

Figure 17: Renewable Resources of Argentina (Armijo und Philibert 2020)

Based on open source available data from NASA, Figure 18 and Figure 19 show wind resources and solar resources in the Province of Rio Negro.

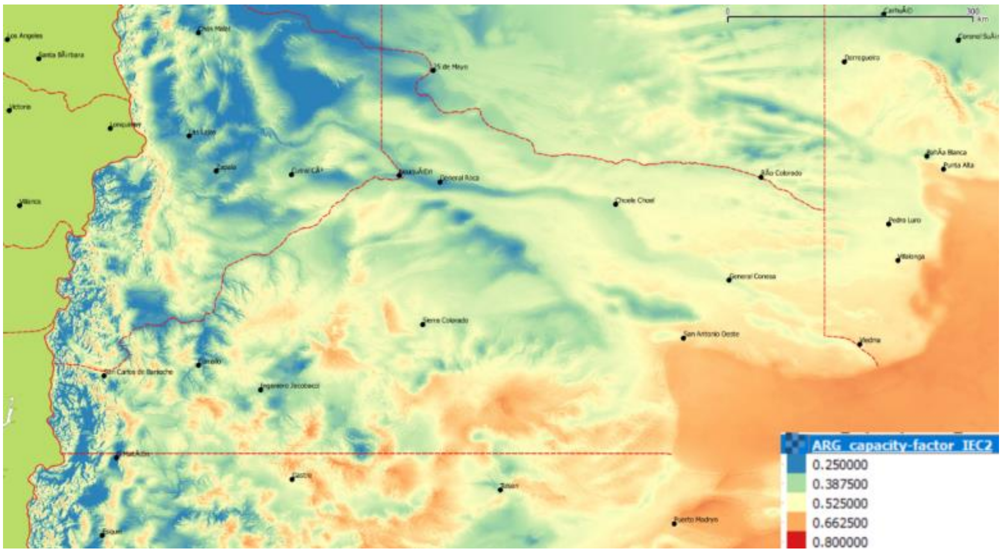

Figure 18: Wind resources of Province Rio Negro

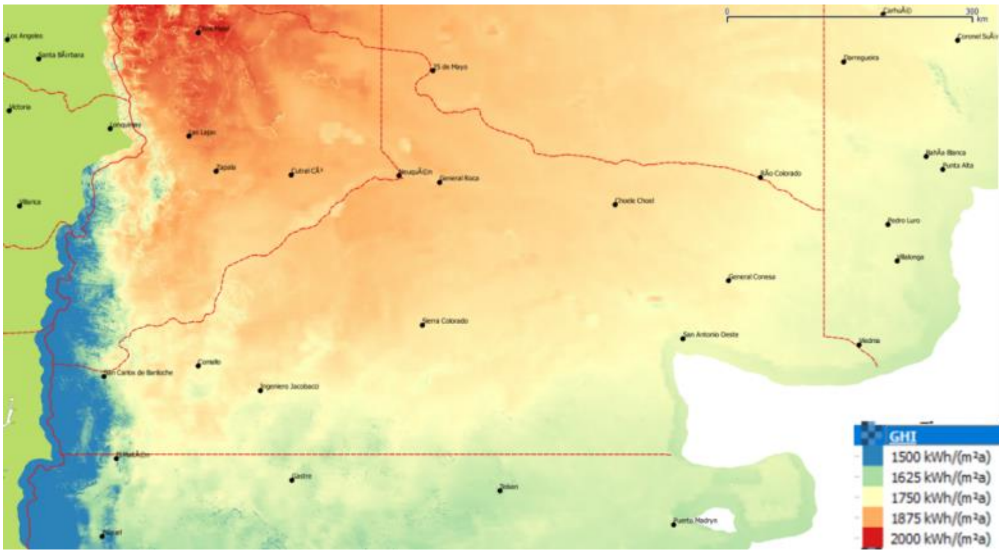

Figure 19: Solar resources of Province Rio Negro

Data regarding wind resources at Idun and Cerro Policia provided by the Government of Río Negro Province are shown in Table 4 and Figure 20.

Table 4: wind resource and energy production analysis for wind farm in Idun

Wind farm name	IDUN 1
Turbine type	GE 3.8-137
Turbine hub height (m)	110
Turbine rated power (kW)	3800
Number of turbines	6
Installed capacity (MW)	22.8
Average air density at average hub elevation of 110 m a.s.l. (kg/m³)	1.187
On-site measurement period (years)	2 (longest)
Number of on-site measurements	1 (total) 2 (applied for wind resource assessment)
Average turbine hub-height wind speed (m/s)	8.65m/s
Net AEP (P50) (GWh/year) - 20 years	103.06
Net AEP (P90) (GWh/year) - 20 years	94.68
Full load equivalent hour (P90) - 20 years	4152.4

Table 4 verifies the good wind conditions of the Province of Rio Negro. The full load hours of this special location are extremely high compared to the average of the world wide wind resources. The average wind speed is 8.65 m/s and thus ideally suited for hydrogen production.

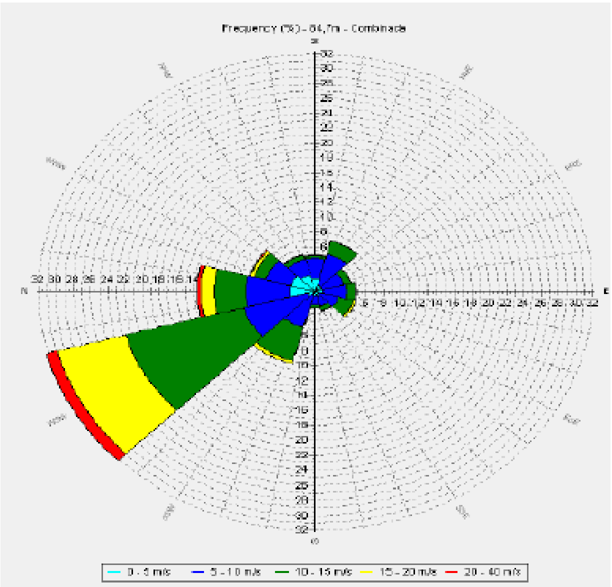

Figure 20: Wind rose for the Cerro Policía site

The wind rose for the potential wind farm site in Cerro Policia shown in Figure 20 illustrates the distribution of wind direction typical for Patagonia. The variance of the wind direction is low, which leads to less shading losses.

The area of Cerro Policia provides one of the best wind resources in the Province of Rio Negro. It is owned by one company, which is owned by the province itself. Land availability is not a limiting factor for such projects.

4.2
Availability and quality of fresh water resources

In the province of Rio Negro, on the border with the province of Neuquen, there is the Rio Limay, which becomes the Rio Negro near Cipoletti and from there flows through the province of Rio Negro to the Atlantic Ocean. An additional water resource is an artificial and 175 km long open canal that takes water from the Rio Negro 40 km away from the town of Coronel Belisle called 'Canal Pomona - San Antonio'. Its capacity is 980,000 m³ (500 l/s) and it is currently operating at 40% of its design capacity.

Figure 21: Water availability in the Province of Rio Negro Argentina

The evaluation of the water analyses showed that the water quality of all samples was sufficient with regard to conductivity, pH value, alkalinity and suspended solids. No additional water treatment is required before feeding the water into the water treatment system of the hydrogen production facility.

4.3
Electrical grid infrastructure

Electricity transport via existing power lines is the cheapest form of transport in comparison to hydrogen or water transport and therefore it is more important to build the electrolysis plant near the water supply and the hydrogen offtake than near the wind farm. However, the power grid must also be able to handle the large amounts of electricity. IEE analyzed the capacity of the electricity grid. The results for the locations are shown in chapter 4.7.

The existing electricity grid is shown in Figure 22 and Figure 23.

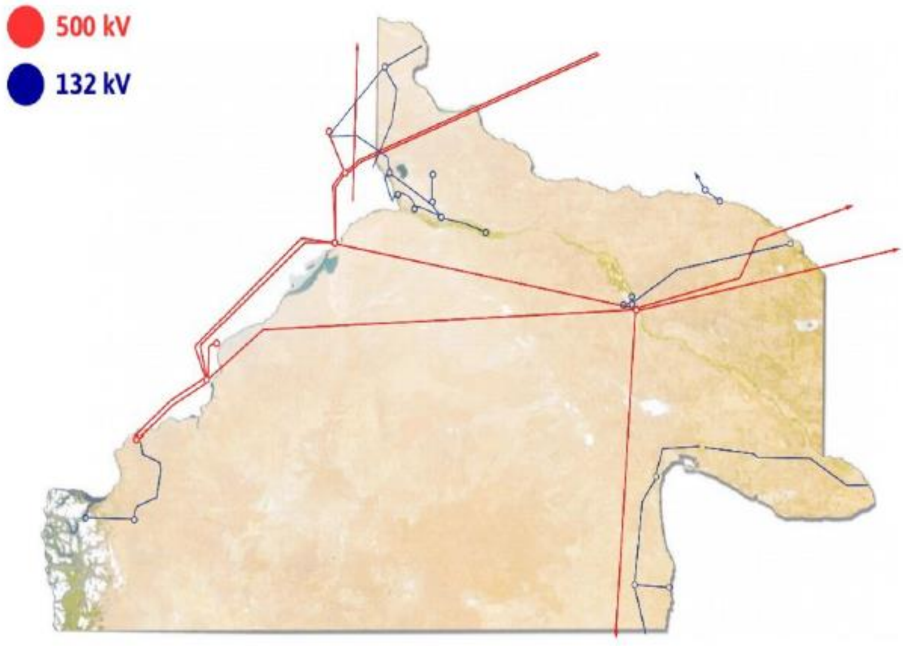

Figure 22: Electrical high voltage grid in province of Rio Negro

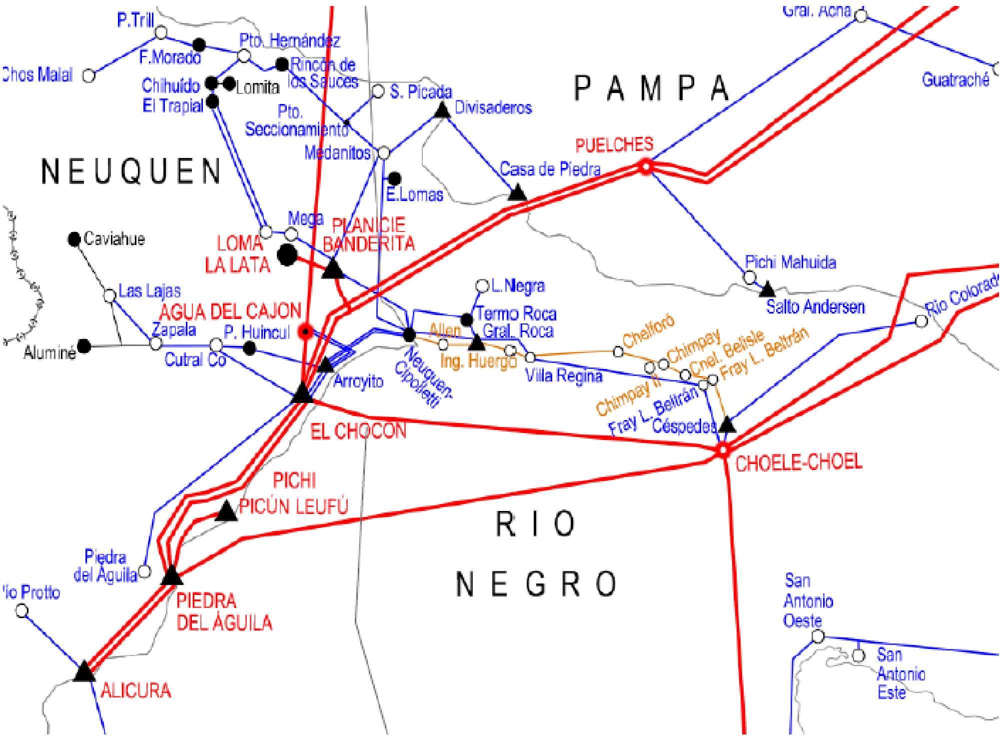

Figure 23: Electrical high voltage grid in province of Rio Negro and around

4.4 Required transport infrastructure

For this study, hydrogen transport by truck and by pipeline was analysed. For the pipeline scenarios, the distance between hydrogen production and consumption was calculated. The road network was used for transport by truck and is shown in Figure 24.

Figure 24: Transport infrastructure of the Province of Rio Negro

4.5
Existing industrial ports

As described above, there are certain requirements for a port where tankers for liquid hydrogen can dock. These are also summarized in Table 5 for demo ships within the HySTRA project and for a future expansion stage. (Collins 2019)

Table 5: Port requirements for docking of liquid hydrogen tankers (Arup Australia Pty Ltd 2019; HySTRA)

Source	Channel Depth/ Depth	Depth Alongside/ Depth	DWT/Tank Capacity	Berth Pocket Size/Ship Dimensions	LOA
Australian Hydrogen Hubs Study	14.2 m	15.7 m	80,000 tonnes	350 m x 90 m	300 m
HySTRA-Project	10.6 m	10.6 m	1,250 m³	116 m x 19 m	116 m

The comparison of the existing ports with the requirements for a port suitable for liquid hydrogen export has shown, that the Port San Antonio Este is the only suitable one in Rio Negro for exporting liquid hydrogen. This port San Antonio Este in its current stage of expansion is suitable for the first liquid hydrogen ships that are limited in scale compared to future LH2 ships, like the one in the HySTRA project with 116 m length over all and therefore the port is suitable for exporting small amounts of hydrogen. A full scale ship (with 300 m length over all) is too large to disembark in the province, but the port could be expanded in the future.

The port terminal has two docks with berths for overseas ships and fishing ships. The quay for the overseas ships is 200 m long and 30 m wide with 2 berths. The dimensions are summarized in the following table.

Table 6: Dimensions for the two oversea berth of the port in San Antonio Este.

Berth	Channel Depth	Depth Alongside	DWT	Berth Pocket Size	LOA
1 (ext)	n/a	13.7 m	n/a	200 m	170 m
2 (int)	n/a	12.2 m	n/a	190 m	147 m

Figure 25 and Figure 26 show the port in San Antonio Este with the two quays. In addition to the oversea quay, the second quay consists of two floating pontoons connected by a metal ramp. Only fishing vessels operate in this dock.

In addition, there are free areas in the port zone where, for example, a liquefaction plant for hydrogen can be built.

Figure 25: Picture of the oversea quay of the port an Antonio Este (http://patagonia-norte.com.ar/index.php/san-antonio-este/76-primer-buque-de-la-temporada-2020-en-puerto-san-antonio-este)

Figure 26: Aerial photograph of the port an Antonio Este. Source: Google Earth.

The Ports in San Antonio Oeste and Punta Colorada are small fishing port basins with a tidal range and are therefore not suitable for overseas ships.

4.6 Potential hydrogen demand in the province

The domestic hydrogen market was evaluated for the use of green hydrogen from a first electrolyser plant in Rio Negro. Since the capacity of the first plant is probably in the range of 100MW, the produced H_2 quantities are too small for the international export of hydrogen - with regard to economic feasibility of liquefaction an electrolysis capacity of 500MW can be seen as the lower limit.

As part of the assessment of the domestic hydrogen market and the current and future hydrogen demand/consumption the mobility sector, gas turbines, industry processes, energy generation were considered. The results of the assessment are that in Rio Negro there are very few industrial hydrogen applications like methanol production, steel production, use of LNG, and refineries as future hydrogen consumers. Alternatives could be the implementation of a hydrogen mobility sector, energy storage, the domestic export to other provinces in Argentina, or the intercontinental export. The critical mass for international export with regard to economic feasibility of liquefaction is 500MW of electrolysis.

Assessment of the current status of the consumption of (grey) hydrogen in Rio Negro by existing industry

Figure 27 shows the population density of Rio Negro province. The busy centres around Bariloche and Cipoletti are visible, as well as the region around the city of Viedma.

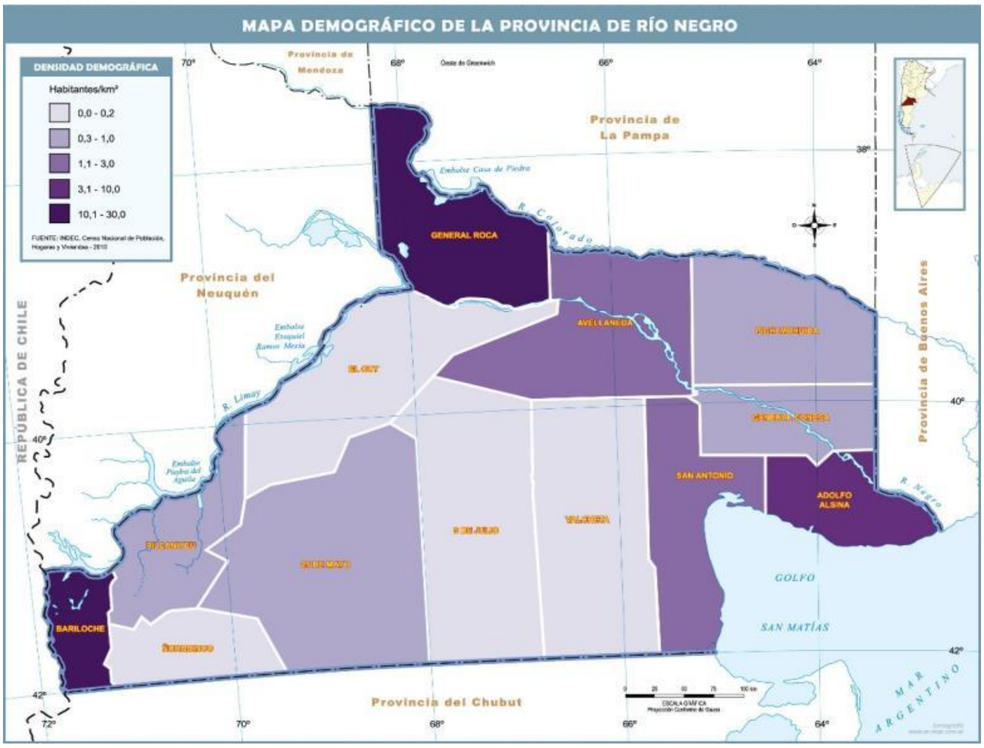

Figure 27: Demographic Map of the Province of Rio Negro Argentina (https://www.gifex.com/America-del-Sur/Argentina/Rio_Negro/index.html)

It must be noted that there is no existing hydrogen infrastructure or transport logistics available in Rio Negro at the moment. There are only small installations in other parts of Argentina like Santa Cruz.

Nevertheless, for this study, based on the agreement with the Government of the Province Rio Negro, hydrogen demand was assumed for the province of Rio Negro and in the region around Cipoletti and in Bahia Blanca in the province of Buenos Aires. The results of the demand and potential offtake analysis are shown in the following tables. In order to evaluate the current hydrogen consumption in the selected regions, the relevant industrial sectors that consume hydrogen and their hydrogen requirements for their processes were determined. In the following the procedure and the used assumptions to determine these hydrogen quantities were described. These estimated amounts of hydrogen are the amounts currently provided by fossil hydrogen. These could potentially be replaced by green hydrogen in the future.

The petrochemical industry sector relies heavily on hydrogen, as it is needed for the treatment of crude oil and as feedstock for products like ammonia. So far, hydrogen is most commonly produced via steam methane reduction (SMR) and therefore is based on fossil fuels.

In refineries, hydrogen is used for processing and enriching carbon-hydrates (e.g. diesel fuel). The amount of hydrogen needed depends on the processes and varies from refinery to refinery. For this study the calculation is based on an average consumption of 5 kg hydrogen per m³ crude oil (Elgowainy 2019) (IG BCE Innovationsforum Energiewende e.V. und Mineralölwirtschaftsverband e.V. 2018). As feedstock, hydrogen is directly used for the production of ammonium and indirect for the production of urea (as ammonium is a feedstock for the urea production).

Conventionally, ammonia is produced via the Haber-Bosch process using methane to get hydrogen. This process, however, emits CO_2 and depends on fossil fuels. Using green hydrogen, SMR becomes an unnecessary production step and CO_2-emissions are reduced. (Otto 2015)

Table 7 presents an overview of existing hydrogen consuming industry in the region of Bahía Blanca. For the region of Cipoletti, existing hydrogen consuming industry are shown in Table 8

Table 7: Hydrogen consuming industry in the region of Bahía Blanca (as base for the estimation of the hydrogen consumption)

Company	Products	Production volume	Source
Dr. Ricardo Eliçabe Refinery	Gasoline, marine fuels, petrochemical feedstock, kerosene, diesel, fuel oil, asphalt, propane, propylene, butane	~30,000 barrel/d (~4,770 m³/d)	(IndustryAbout 2019) (Energías de mi País 2021)
Dow Chemical	Ethylene, propylene	730,000 t/a	(Baida 2019) (U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy 2019) (Martin 2019)
TGS	Ethane, propane, butane, petrol	Ethane – 283,000 t Propane – 367,000 t Butane – 250,000 t Petrol – 121,000 t Natural gas storage – 16,600 m³	(tgs 2020)
Profertil	Urea, ammonia	Urea – 1.32 mil. t/a Ammonia – 790,000 t/a ammonia	(Profertil 2021) (West 2018)

Table 8: Hydrogen consuming industry in the region of Cipoletti (as base for the estimation of the hydrogen consumption)

Company	Products	Production volume	Source
Refinería YPF (Plaza Huincul – 110 km west of Cipolletti)	Gasoline, diesel, methanol, kerosene	Processing 4,000 m³ oil per day Methanol – 36,000 t/month Light fuel oil – 56,000 t/month	(YPF 2016) (Río Negro 2019)
Fox Petrol (Senillosa – 40 km west of Cipoletti)	Gasoline, diesel, turpentine, solvents	12,000 m³/month (400 m³/d)	(Fox Petrol S.A. 2021)
YPF Loma Campana (Añelo – 100 km north-west of Cipolletti)	Crude oil processing	8,000-10,000 m³/d	(rionegro.com 2020)
YPF La Amarga Chica (near Añelo – 115 km north-west of Cipolletti)	Oil equivalents	60,000 barrels/d (9,540 m³/d) in 2022	(ns energy 2018)

Calculation of the hydrogen demand based on the evaluation of hydrogen consuming industry

As mentioned above, these industrial processes consume hydrogen. The demand of hydrogen was calculated for each industrial process with the above mentioned assumptions. A substitution from grey to green hydrogen would be possible in the future. The demands for green hydrogen in future, based on the current grey hydrogen demand, at the listed industrial spots as well as the potential reduction of CO_2 emissions are shown in Table 9.

Table 9: Potential green hydrogen consumption in the industry in the regions of Bahía Blanca and Cipoletti (based on on calculations of the current grey hydrogen consumption)

Company	Production volume	Potential green H2 consumption	Potential reduction of CO_2-emissions
Dr. Ricardo Eliçabe Refinery **(Bahía Blanca)**	~30,000 barrel/d (~4,770 m³/d)	8,705 t/a	
Dow Chemical **(Bahía Blanca)**	730,000 t/a		760,000 t/a
Profertil **(Bahía Blanca)**	Ammonia – 790,000 t/a Urea – 1.32 mil. t/a	140,271 t/a 132,915 t/a	1,480,000 t/a 1,402,386 t/a
Refinería YPF **(Plaza Huincul – 110 km west of Cipolletti)**	Processing 4,000 m³ oil/day Methanol – 36,000 t/month Light fuel oil – 56,000 t/month	81,541 t/a	220,752 t/a
Fox Petrol **(Senillosa – 40 km west of Cipoletti)**	12,000 m³/month (400 m³/d)	730 t/a	
YPF Loma Campana **(Añelo – 100 km north-west of Cipolletti)**	8,000-10,000 m³/d	14,600-18,250 t/a	
YPF La Amarga Chica **(near Añelo – 115 km north-west of Cipolletti)**	60,000 barrels/d (9,540 m³/d) in 2022	17,410 t/a	

Estimation of the hydrogen requirements for mobility sector

In addition to industrial processes, the mobility sector in general is a "low hanging fruit" for the use of green hydrogen in short-term because the market price for hydrogen as fuel (around 11$/kg H_2 at the pump in the EU) is the highest. However, due to the good availability of natural gas and the low gas price in Argentina, no broad application of green hydrogen in the mobility sector in Argentina in short-term usage is to be expected. Nevertheless, the following explanations should give an indication of which hydrogen consumption quantities can be expected in the mobility sector for Bahia Blanca and Cipoletti as example regions.

In the mobility sector, there are many different types of vehicles. In this study, it has been focused on cars, trucks and busses as well as garbage trucks. Table 10 shows the assumptions for calculation of the demand for hydrogen in the case for cars.

Table 10: Assumptions on hydrogen mobility

	Hydrogen	Gasolin	Source
Heat value [kWh/kg]	33.3	12	(Funke)
Density [kg/m³] of hydrogen at 700 bar	40	740	(Ingenieurbüro für Brennstoffzelle, Wasserstofftechnologie und Elektromobilität (EMCEL) 2019)
Consumption cars [kg/100 km]	0.9	5.7	(Altenburg et al. 2017) (Kords 2021)
Consumption busses and trucks [kg/100 km]	10	33,2	(Altenburg et al. 2017) (Webfleet Solutions 2020)
Cost [€/kg]	3.50 €	0.99 €	(globalpetrolprices.com)
Cost [€/100 km]	3.15 €	5.74 €	

The following Table 11 shows the figures determined for cars and vehicles for Bahia Blanca and Cipioletti and the number of buses and trucks for the entire Rio Negro Province. There were no numbers for cars for the entire Rio Negro Province.

Table 11: Numbers of different vehicles in Bahia Blanca, cipoletti and Rio Negro Province (if available).

	Numbers	Source
Kilometers travelled per year car	12,322	(iProfesional 2019)
Number of vehicles in Cipoletti - cars	11,625	(Kania) (Patagonia.com.ar)
Number of vehicles in Bahia Blanca - cars	47,895	(Kania) (citypopulation.de 2019)
Kilometers driven by trucks per year	81,000	(turboseguros.com)
Number of vehicles in Rio Negro – busses and trucks	7,965	(autoblog.com.ar 2017)
Number of vehicles in Cipoletti – garbage trucks	11	(Kaltenbach et al. 2018) (ASG Wesel)
Number of vehicles in Bahìa Blanca – garbage trucks	47	(Kaltenbach et al. 2018) (ASG Wesel)

Based on the numbers given in Table 10 and Table 11, the potential quantities of green hydrogen that could be consumed in the mobility sector are shown in table 12

Table 12: Calculation of the potential consumption of hydrogen in the mobility sector

	Hydrogen
Demand for hydrogen Cipoletti [t/year] - cars	1,289
Demand for hydrogen Bahìa Blanca [t/year] - cars	5,311
Demand for hydrogen Cipoletti [t/year] - garbage trucks	9.2
Demand for hydrogen Bahìa Blanca [t/year] – garbage trucks	37.8
Demand for hydrogen in Rio Negro [kg/year] – trucks and busses	87,216

With the assumption that there are 595,520 passenger cars in Bahía Blanca and Cipoletti, there is the need for 6,600t of hydrogen per year.

Concerning busses and trucks, there are almost 8,000 vehicles in the region of Rio Negro, which could consume more than 87,000t of hydrogen per year.
For these selected consumers 93,875 t of hydrogen in the mobility sector could be sold, assuming, that all vehicles considered change from fossil fuels to hydrogen.

This analysis is generic. For a detailed analysis of hydrogen usage for mobility, information e.g. certain type of vehicle (busses, trucks, trains, cars), number of vehicles, driven distance per vehicle for a region will be necessary.

4.7
Analysis of potential electrolyser sites

The three locations analysed for building an electrolyser plant below were recommended by the Government of the Province Rio Negro. In the following sub sections all three locations will be introduced with special regards to water accessibility, land ownership, connection to the electrical grid, infrastructure, and the geological factors. In Figure 28 the locations as well as port San Antonio Oeste in the San Matías Gulf are marked on a map of the eastern part of the Río Negro province: “El Solito”, “Pomona”, “Laguna de la Retención”. In addition to the analysis of the above-mentioned sites, a limited assessment was carried out for “El Chocón”.

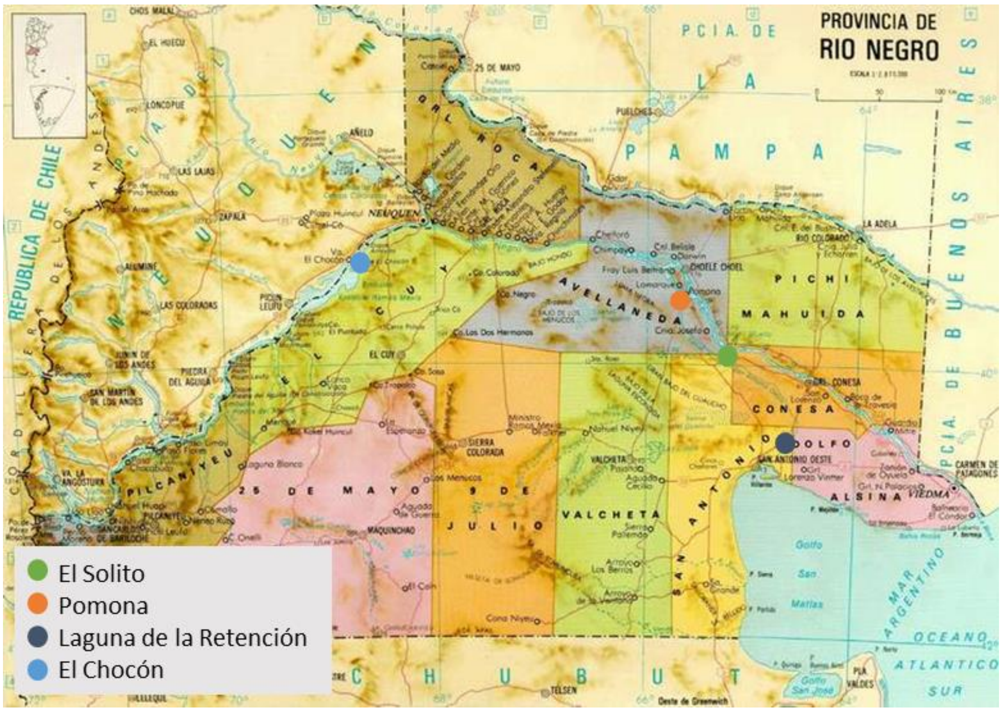

Figure 28: Potential sites for the electrolyser and electricity generation evaluated in this study (map based on https://www.gifex.com/America-del-Sur/Argentina/Rio_Negro/index.html)

4.7.1 El Solito

The "El Solito" site (Figure 29) is located between the cities of Pomona and General Conesa. It is located 2.5 km off the national route RN250 and is connected with it via gravel road. The RN2 is located within 19 km. This piece of land is of the soil type of a meadow (spanish: mallín) and the surface of the area close to the Río Negro is plane.

Its distance to the port San Antonio Este amounts to 145 km. Within 3.2 km distance there is a 13.2/33/132 kV transformer station in the finale phase of construction and a 132 kV transmission line is under construction (this line does not fulfill the required transportation capacity of this 100 MW project). To reach the nearest 500 kV transmission line, investments have to be arranged to build a connection and a 132/500 kV transformer station at the connection site.

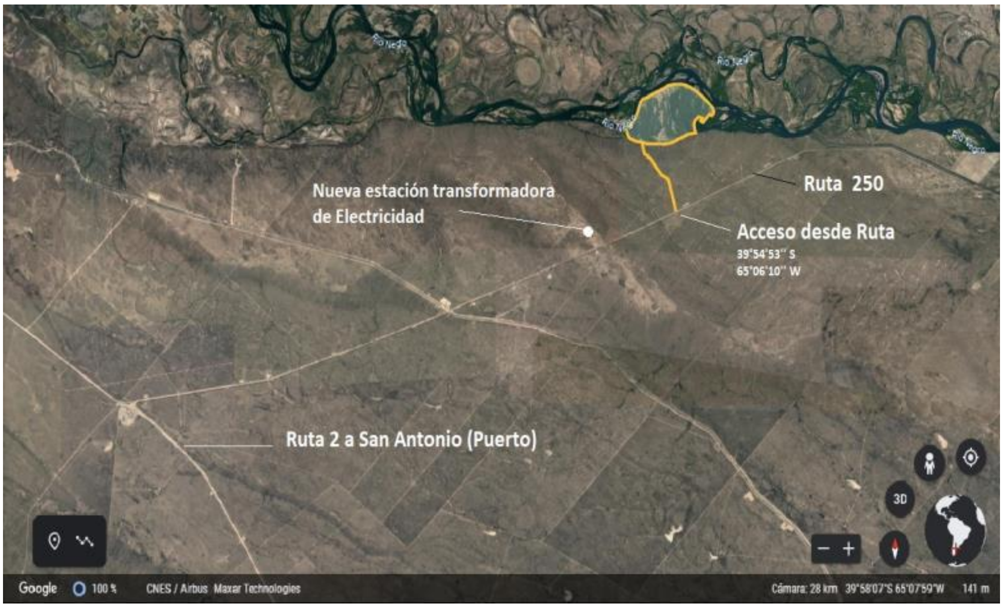

Figure 29: Satellite image of the proposed location "El Solito"

4.7.2 Pomona

The proposed area (Figure 30) in close proximity to the city of Pomona and has an area of 5,100 hectares with a plane surface. The national route RN250 is about 13 km away. The site's distance to the San Antonio port amounts to 230 km.
Within 10 km distance there is a 500/132 kV transformer station. The Pomona – San Antonio Canal as source for water is 11 km away. Technical facilities near to the site are a thermo-electrical power plant with a generation capacity of 8.28 MW and a privately owned wind farm (113 MW generation capacity).

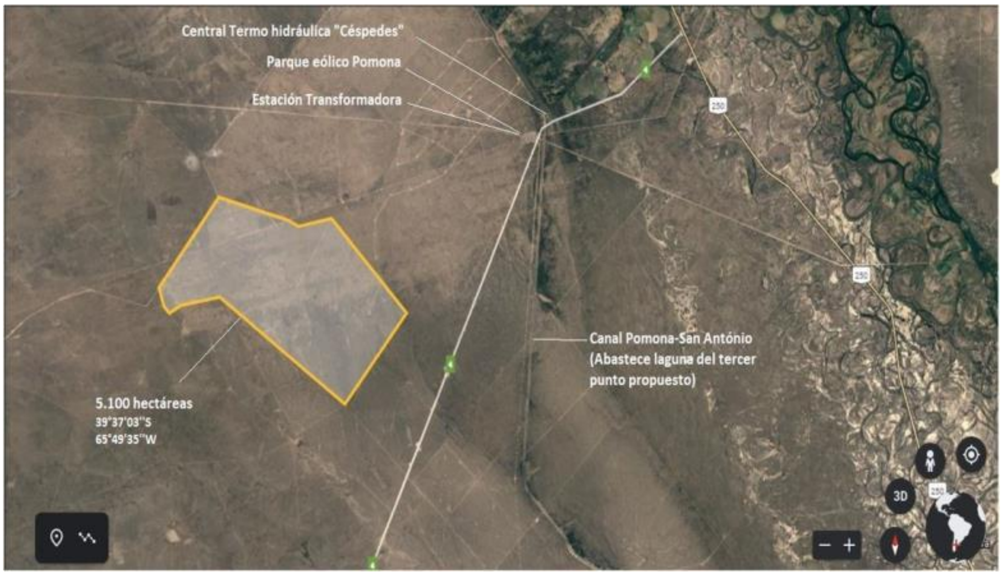

Figure 30: Satellite image of the proposed location "Pomona"

4.7.3 Laguna de la Retención

The site “Laguna de la Retención” (Figure 31) is the closest to the sea. The distance to the San Antonio harbor is 38 km with 27 km of paved street and 11 km of gravel road with maintenance. The 560 hectare big area lies 110 meters above sea level. The surface is even with only low native vegetation.
A 132 kV high-voltage transmission line is within 9.5 km distance to the N°3 federal road. Additionally, there are plans for a 500 kV transmission line through this area.
A water reservoir for Laguna de la Retención is available within the proposed area. This artificial lagoon has a capacity of 980,000 m³ and is fed by the Pomona – San Antonio Canal; it’s current flow capacity amounts to 550 liters per second and can be increased through corresponding investments.

Figure 31: Satellite image of the proposed location "Laguna de la Retención"

5
Overview and description of the scenarios analysed

As part of the project, different scenarios for the implementation of green hydrogen production in Rio Negro were calculated. The calculation of different scenarios and the variation of several aspects is necessary to determine the most economical option for the implementation of a first plant in Rio Negro.

5.1
Overview and description of the scenarios

5.1.1 Location of hydrogen and electricity production

The four locations analysed for hydrogen production in Rio Negro Province are

1) Pomona
2) El Solito
3) Laguna de la Retención SAO
4) El Chocón

For these locations, the availability and possible connection of the electricity grid as well as the availability and possible connection of water source were determined. The distances to the electricity grid, to the water supply, to the consumer or the port were examined and then used for the calculation of the hydrogen production costs.

As a water source the Rio Negro River or the canal between Pomona and San Antonio Oeste are considered. The current water flow rate of the canal between Pomona and San Antonio Oeste is 500 l/s which represents only 40% of its full capacity. The capacity of the canal is sufficient for supplying the electrolyser (maximum 200 m^3/h respectively 11% of canal capacity for a 500 MW electrolyser and full load). It is important to mention, that there will be no shortage of drinking water in case of supplying the hydrogen production from the canal.
Based on the available water analysis, the water quality is sufficient for the use in an electrolyser so that a simple water treatment with rake or sieve and suspended matter filter will be sufficient and no special water treatment for the river water to achieve tap water quality is necessary.

The following renewable energy options for electricity production are considered:
- The planned wind farm Cerro Policía is considered to be the power source for all electrolysis locations.
- Wind farm and hybrid plant at the site of the electrolyser.
  - The wind potential and a wind farm at the site of the electrolyser will be taken into account.
  - A hybrid plant (combined wind farm and PV plant) is calculated for each site of the electrolyser location
- A hybrid plant as a combination of the wind farm Cerro Policía and PV is taken into account. With the hybrid plant, the full load hours of the electrolyser increase.

When the electricity is generated in Cerro Policía, the existing electricity grid (500 kV) is always used for electricity transport to the electrolyser location, both for the electricity from a wind farm as well as in the case of a hybrid system.

Location of electrolyser: **Pomona**
- Information on grid connection for wind farm and hybrid system Cerro Policía: Use of existing electricity grid (500 kV), construction of 9.8 km of electricity line up to the 500/132 kV substation.
- Information on grid connection for wind farm and hybrid system in Pomona: Direct connection between wind farm or hybrid plant and electrolysis, installation of a substation
- Information on water supply: Using the existing canal between Pomona and San Antonio Oeste, construction of 11 km of additional canal; Water quality sufficient

Location of electrolyser: **El Solito**
- Information on grid connection for wind farm and hybrid system Cerro Policía: Use of existing electricity grid (500 kV), construction of 75 km of electricity line and grid connection.
- Information on grid connection for wind farm and hybrid System in El Solito: Direct connection between wind farm or hybrid plant and electrolyser, installation of a substation
- Information on water supply: Rio Negro river; Water quality sufficient

Location of electrolyser: **Laguna de la Retención**
- Information on grid connection for wind farm and hybrid system Cerro Policía:
  - 500 MW in 2030: It is assumed that a 500 kV line will be built until 2030. Within the project, a grid connection with a substation is planned.
  - 100 MW in 2025: It is assumed that the 132 kV line can be used. Within the project, a grid connection with a substation including 9.5 km of transmission line to the existing grid is planned.
- Information grid connection for wind farm and hybrid system in Laguna de la Retención: Direct connection between wind farm or hybrid plant and electrolyser, installation of a substation
- Information water supply: Direct connection to Pomona-San Antonio Oeste canal; Water quality sufficient

Location of electrolyser: **El Chocón**
- Information on grid connection for wind farm and Hybrid system Cerro Policía: Use of existing electricity grid (500 kV), construction of 5 km of electricity line up to the 500/132 kV substation.
- Information on water supply: Rio Limay; Water quality sufficient

5.1.2 Domestic Scenario

The domestic scenario addresses the initial hydrogen production technology role out in the region – but starting with a relevant project scale in order to achieve low specific cost already in an early phase.

In Rio Negro the hydrogen consumption of the industry is low. Typical industrial large scale hydrogen demands such as methanol production, steel production, use of LNG or refineries are not present as future hydrogen consumers. Alternatives could be the implementation of using hydrogen as a fuel in the transport sector, for energy storage, the national export to other provinces in Argentina or the international intercontinental export (see export scenario). The use of hydrogen in the transport sector is a "low hanging fruit" due to the high value of hydrogen as fuel.

The domestic scenarios consider the national export to other provinces in Argentina with relevant industrial hydrogen demand. As location for hydrogen consumption

Bahia Blanca and Cipolletti are considered. The location of the hydrogen consumption is used for the calculation of transport capacities, distances and duration.

The following conditions are assumed for all electrolyser locations for domestic scenarios
- The electrolyser capacity is 100 MW. This is a sufficient size for a pilot plant and the costs are moderate.
- The year of installation is 2025, because there are commercial designs for 100 MW electrolyser systems available, so that an implementation in 2025 is realistic.
- Consumer locations
  - Bahía Blanca
  - Cipolletti
- Different transport options for the hydrogen from the electrolysis to the consumer are considered, see chapter „Transport of hydrogen“.

For Chocón only, domestic scenarios are calculated with the use of the hydrogen in nearby refineries in Plaza Huincul and Bahia Blanca. For the usage of hydrogen in the mobility sector transport to Cipolletti is calculated.

5.1.3 Export Scenario

For the evaluation of the export option of green hydrogen from Rio Negro, two export scenarios are calculated. These scenarios differ in that Germany and Japan are the target countries for the hydrogen export. The consumer country is relevant for calculation of transport capacities, distances and duration.

The following conditions are assumed for all electrolyser locations:
- The electrolyser capacity is 500 MW. The critical mass for international export with regard to economic feasibility of liquefaction is ≥ 500MW of electrolysis.
- The year of completion of the installation is 2030, because the implementation of 500 MW systems is not plausible before 2030 due to ramp up of electrolysis production and hydrogen economy
- Consumer countries
  - Germany
  - Japan
- The chosen export port is San Antonio Este: The evaluation of the data regarding the ports has shown, that the Port San Antonio Este is the only suitable one in Rio Negro for exporting hydrogen, see also chapter "port".

For export scenarios the costs are calculated taking into account
- Pipeline from electrolyser to the liquefaction close to the port
- Storage for gaseous hydrogen to enable continuous liquefaction
- Liquefaction
- Storage for liquid hydrogen
- Ships

<u>Assumptions for transport</u>
- Capacity per ship: 2500 t LH2
- Transport time to Germany: 15 days
- Transport time to Japan: 23 days
- Time for loading and unloading: 1 day each
- Cost per ship: 85 Mio. €

Table 13: Number of ships needed per export destination and system of electricity production

	number of ship
Wind farm Cerro Policía	GER: 2 JP: 3
Wind farm Laguna de la Retención	GER 2 JP: 3
Hybrid plant Cerro Policía	GER 3 JP: 4
Hybrid plant Laguna de la Retención	GER 3 JP: 4

5.1.4 Transport of hydrogen

Various options are possible for the transport of hydrogen from the production site to the consumer or the port.
The most economical variant depends on the amount of hydrogen to be transported and the distance.

- Transport option for export scenarios:
  - According to the analysis of available, the only economic transport option for the hydrogen amount of a 500 MW plant is the transport by pipeline rather than by trucks. Therefore, in the export scenarios a pipeline from the production site to the port is be calculated.
  - The hydrogen is liquefied at the port and then transported to Germany or Japan by ship.
  - The costs of pipeline, liquefaction and ships are considered.
- Transport option for domestic scenarios:
  - The transport by pipeline and trucks are taken into account. Trucks are considered as transport vehicle for the hydrogen. The assumed pressure in the hydrogen vessels of the trailer is 500 bar. Trains are not taken into account here due to the very site specific conditions of rail infrastructure and the complexity of the implementation of this solution in and so far unspecified regulatory framework in Argentina. Technical information on transport options by train is provided in the "transport" chapter.
  - For the pipeline transport, the construction of a new hydrogen pipeline is calculated. The transmission pressure is 100 bar.
  - Because of the high investment costs of a liquefaction, the smallest production capacity for a liquefaction is 500 MW. Therefore, a liquefaction is not considered for the domestic scenarios.

Annual cost of transport of hydrogen

- The cost depend on
  - The distance from the location of the electrolyser to the location of consumption. The distances are calculated for each scenario.
  - The transport technology
  - The hydrogen production quantity (according to the electricity generation and the resulting full load hours).

5.2 Nomenclature of the scenarios

The following scenario nomenclature has been established for this study in order to define and distinguish the scenarios by their titles. The composition of the abbreviations for the various aspects and variations has been defined as follows:

- Name of electrolyser location
  - Pomona = Po
  - El Solito = ElS
  - Laguna de la Retenció= LR
  - Chocón = Cho
- Name of electricity generation location
  - Wind farm = WF
  - hybrid plant = HP
    → Example: Wind farm in Cerro Policía = WF/CP
- Export or domestic scenario
  - Export-500
  - Domestic-100
- Transport technology
  - pipeline
  - truck
  - ship (only in export scenario, ship transport includes liquefaction)
- Consumer Location
  - Germany = GER
  - Japan = JP
  - Cipolletti = Cip
  - Bahai Blanca = BB
  - Plaza Huincul = PH
- Example: Po-WF/CP-Export-500-ship-GER (= Electrolyser in Pomona, wind farm in Cerro Policía, export scenario with ship transport to Germany)

Table 14: Overview and names of the scenarios with hydrogen production site Pomona

Overview and description of the scenarios analysed

Name	Electro-lyser location	Electricity generation	Export or domestic Scenario	Consumer country or domestic Market	Transport of hydrogen
Po-WF/CP-export-500-ship-GER	Pomona	Wind farm Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
Po-WF/CP-export-500-ship-JP	Pomona	Wind farm Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
Po-WF/CP-domestic-100-pipeline-Cip	Pomona	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
Po-WF/CP-domestic-100-truck-Cip	Pomona	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Truck
Po-WF/CP-domestic-100-pipeline-BB	Pomona	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
Po-WF/CP-domestic-100-truck-BB	Pomona	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
Po-WF/Po-export-500-ship-GER	Pomona	Wind farm Pomona	Export Scenario	Germany	pipeline to port, liquefaction, ship
Po-WF/Po-export-500-ship-JP	Pomona	Wind farm Pomona	Export Scenario	Japan	pipeline to port, liquefaction, ship
Po-WF/Po-domestic-100-pipeline-Cip	Pomona	Wind farm Pomona	Domestic Scenario	Cipolletti	Hydrogen pipeline
Po-WF/Po-domestic-100-truck-Cip	Pomona	Wind farm Pomona	Domestic Scenario	Cipolletti	Truck
Po-WF/Po-domestic-100-pipeline-BB	Pomona	Wind farm Pomona	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
Po-WF/Po-domestic-100-truck-BB	Pomona	Wind farm Pomona	Domestic Scenario	Bahía Blanca	Truck
Po-HP/CP-export-500-ship-GER	Pomona	Hybrid plant Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
Po-HP/CP-export-500-ship-JP	Pomona	Hybrid plant Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
Po-HP/CP-domestic-100-pipeline-Cip	Pomona	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
Po-HP/CP-domestic-100-truck-Cip	Pomona	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Truck
Po-HP/CP-domestic-100-pipeline-BB	Pomona	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
Po-HP/CP-domestic-100-truck-BB	Pomona	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
Po-HP/Po-export-500-ship-GER	Pomona	Hybrid plant Pomona	Export Scenario	Germany	pipeline to port, liquefaction, ship
Po-HP/Po-export-500-ship-JP	Pomona	Hybrid plant Pomona	Export Scenario	Japan	pipeline to port, liquefaction, ship
Po-HP/Po-domestic-100-pipeline-Cip	Pomona	Hybrid plant Pomona	Domestic Scenario	Cipolletti	Hydrogen pipeline
Po-HP/Po-domestic-100-truck-Cip	Pomona	Hybrid plant Pomona	Domestic Scenario	Cipolletti	Truck
Po-HP/Po-domestic-100-pipeline-BB	Pomona	Hybrid plant Pomona	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
Po-HP/Po-domestic-100-truck-BB	Pomona	Hybrid plant Pomona	Domestic Scenario	Bahía Blanca	Truck

Overview and description of the scenarios analysed

Table 15: Overview and names of the scenarios with hydrogen production site El Solito

Name	Electro-lyser location	Electricity generation	Export or domestic Scenario	Consumer country or domestic Market	Transport of hydrogen
ElS-WF/CP-export-500-ship-GER	El Solito	Wind farm Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
ElS-WF/CP-export-500-ship-JP	El Solito	Wind farm Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
ElS-WF/CP-domestic-100-pipeline-Cip	El Solito	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
ElS-WF/CP-domestic-100-truck-Cip	El Solito	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Truck
ElS-WF/CP-domestic-100-pipeline-BB	El Solito	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
ElS-WF/CP-domestic-100-truck-BB	El Solito	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
ElS-WF/ElS-export-500-ship-GER	El Solito	Wind farm El Solito	Export Scenario	Germany	pipeline to port, liquefaction, ship
ElS-WF/ElS-export-500-ship-JP	El Solito	Wind farm El Solito	Export Scenario	Japan	pipeline to port, liquefaction, ship
ElS-WF/ElS-domestic-100-pipeline-Cip	El Solito	Wind farm El Solito	Domestic Scenario	Cipolletti	Hydrogen pipeline
ElS-WF/ElS-domestic-100-truck-Cip	El Solito	Wind farm El Solito	Domestic Scenario	Cipolletti	Truck
ElS-WF/ElS-domestic-100-pipeline-BB	El Solito	Wind farm El Solito	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
ElS-WF/ElS-domestic-100-truck-BB	El Solito	Wind farm El Solito	Domestic Scenario	Bahía Blanca	Truck
ElS-HP/CP-export-500-ship-GER	El Solito	Hybrid plant Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
ElS-HP/CP-export-500-ship-JP	El Solito	Hybrid plant Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
ElS-HP/CP-domestic-100-pipeline-Cip	El Solito	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
ElS-HP/CP-domestic-100-truck-Cip	El Solito	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Truck
ElS-HP/CP-domestic-100-pipeline-BB	El Solito	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
ElS-HP/CP-domestic-100-truck-BB	El Solito	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
ElS-HP/ElS-export-500-ship-GER	El Solito	Hybrid plant El Solito	Export Scenario	Germany	pipeline to port, liquefaction, ship
ElS-HP/ElS-export-500-ship-JP	El Solito	Hybrid plant El Solito	Export Scenario	Japan	pipeline to port, liquefaction, ship
ElS-HP/ElS-domestic-100-pipeline-Cip	El Solito	Hybrid plant El Solito	Domestic Scenario	Cipolletti	Hydrogen pipeline
ElS-HP/ElS-domestic-100-truck-Cip	El Solito	Hybrid plant El Solito	Domestic Scenario	Cipolletti	Truck
ElS-HP/ElS-domestic-100-pipeline-BB	El Solito	Hybrid plant El Solito	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
ElS-HP/ElS-domestic-100-truck-BB	El Solito	Hybrid plant El Solito	Domestic Scenario	Bahía Blanca	Truck

Table 16: Overview and names of the scenarios with hydrogen production site Laguna de la Retención SAO

Name	Electro-lyser location	Electricity generation	Export or domestic Scenario	Consumer country or domestic Market	Transport of hydrogen
LR-WF/CP-export-500-ship-GER	Laguna de la Retención	Wind farm Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
LR-WF/CP-export-500-ship-JP	Laguna de la Retención	Wind farm Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
LR-WF/CP-domestic-100-pipeline-Cip	Laguna de la Retención	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
LR-WF/CP-domestic-100-truck-Cip	Laguna de la Retención	Wind farm Cerro Policía	Domestic Scenario	Cipolletti	Truck
LR-WF/CP-domestic-100-pipeline-BB	Laguna de la Retención	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
LR-WF/CP-domestic-100-truck-BB	Laguna de la Retención	Wind farm Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
LR-WF/LR-export-500-ship-GER	Laguna de la Retención	Wind farm L. d. l. Retención	Export Scenario	Germany	pipeline to port, liquefaction, ship
LR-WF/LR-export-500-ship-JP	Laguna de la Retención	Wind farm L. d. l. Retención	Export Scenario	Japan	pipeline to port, liquefaction, ship
LR-WF/LR-domestic-100-pipeline-Cip	Laguna de la Retención	Wind farm L. d. l. Retención	Domestic Scenario	Cipolletti	Hydrogen pipeline
LR-WF/LR-domestic-100-truck-Cip	Laguna de la Retención	Wind farm L. d. l. Retención	Domestic Scenario	Cipolletti	Truck
LR-WF/LR-domestic-100-pipeline-BB	Laguna de la Retención	Wind farm L. d. l. Retención	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
LR-WF/LR-domestic-100-truck-BB	Laguna de la Retención	Wind farm L. d. l. Retención	Domestic Scenario	Bahía Blanca	Truck
LR-HP/CP-export-500-ship-GER	Laguna de la Retención	Hybrid plant Cerro Policía	Export Scenario	Germany	pipeline to port, liquefaction, ship
LR-HP/CP-export-500-ship-JP	Laguna de la Retención	Hybrid plant Cerro Policía	Export Scenario	Japan	pipeline to port, liquefaction, ship
LR-HP/CP-domestic-100-pipeline-Cip	Laguna de la Retención	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Hydrogen pipeline
LR-HP/CP-domestic-100-truck-Cip	Laguna de la Retención	Hybrid plant Cerro Policía	Domestic Scenario	Cipolletti	Truck
LR-HP/CP-domestic-100-pipeline-BB	Laguna de la Retención	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
LR-HP/CP-domestic-100-truck-BB	Laguna de la Retención	Hybrid plant Cerro Policía	Domestic Scenario	Bahía Blanca	Truck
LR-HP/LR-export-500-ship-GER	Laguna de la Retención	Hybrid plant L. d. l. Retención	Export Scenario	Germany	pipeline to port, liquefaction, ship
LR-HP/LR-export-500-ship-JP	Laguna de la Retención	Hybrid plant L. d. l. Retención	Export Scenario	Japan	pipeline to port, liquefaction, ship
LR-HP/LR-domestic-100-pipeline-Cip	Laguna de la Retención	Hybrid plant L. d. l. Retención	Domestic Scenario	Cipolletti	Hydrogen pipeline
LR-HP/LR-domestic-100-truck-Cip	Laguna de la Retención	Hybrid plant L. d. l. Retención	Domestic Scenario	Cipolletti	Truck
LR-HP/LR-domestic-100-pipeline-BB	Laguna de la Retención	Hybrid plant L. d. l. Retención	Domestic Scenario	Bahía Blanca	Hydrogen pipeline
LR-HP/LR-domestic-100-truck-BB	Laguna de la Retención	Hybrid plant L. d. l. Retención	Domestic Scenario	Bahía Blanca	Truck

Table 17: Overview and names of the scenarios with hydrogen production site Chocón

Name	Electrolyser location	Electricity generation	Export or domestic Scenario	Domestic Market	Transport of hydrogen
Cho-WF/CP-domestic-100-pipeline-PH	Chocón	Wind farm Cerro Policía	Domestic Scenario	Refinery in Plaza Huincul	Hydrogen pipeline
Cho-WF/CP-domestic-100-truck-PH	Chocón	Wind farm Cerro Policía	Domestic Scenario	Refinery in Plaza Huincul	Truck
Cho-WF/CP-domestic-100-pipeline-BB	Chocón	Wind farm Cerro Policía	Domestic Scenario	Refinery in Bahía Blanca	Hydrogen pipeline
Cho-WF/CP-domestic-100-truck-BB	Chocón	Wind farm Cerro Policía	Domestic Scenario	Refinery in Bahía Blanca	Truck
Cho-WF/CP-domestic-100-pipeline-Cip	Chocón	Wind farm Cerro Policía	Domestic Scenario	Mobility in Cipolletti	Hydrogen pipeline
Cho-WF/CP-domestic-100-truck-Cip	Chocón	Wind farm Cerro Policía	Domestic Scenario	Mobility in Cipolletti	Truck

6
Cost analysis and results of hydrogen production costs

6.1
Methodology of LCOH calculation

The economic performance of investments can be established with various methods, e.g. on the basis of net present value, of annuity, of internal rate of return, of amortization, or using a full budget plan. The annuity method used for this study is based on the German guidelines VDI 2067 and VDI 6025 (Verein deutscher Ingenieure VDI 2012a, 2012b). Below follows a summary of how to apply the method.

With the annuity method, the non-periodic payments and periodic payments with changing amounts are transformed over an assessment period into constant periodic payments. The annuity is the determined common constant periodic payment.
The annuity factor “a” takes into account the interest rate “i” and the observation period “T”. Additionally the annuity method includes cost escalation rates “r” for the different cost groups, to respect e.g. inflation.

Costs can generally be divided into two types - non-periodic disbursements and so-called recurring payments. The costs are furthermore subdivided into the following cost groups
- capital-related,
- demand-related,
- operation-related, and
- other costs.

Table 18 Examples for cost types

capital-related costs	demand-related costs	operation-related costs	other costs
Investments for the plant	Electricity costs (if not calculated as investment)1	Maintenance costs	Insurance costs
Planning of the plant		Labour costs	Costs of demolition and disposal
Infrastructure and installation		Repair costs	

In case of determining the advantageousness of a potential project by means of the annuity method, the revenues are also converted into an annuity. The difference between the annuity of the proceeds and the sum of the annuities of the capital-related, demand-related, operation-related, and other costs equals the total annuity of all costs of an installation.

[1] The costs for the electricity can be considered as investment costs or as periodic payments. The first scenario assumes that the project owner builds the windfarm and the elctrolyser. He pays the CAPEX (capital-related costs) and the OPEX (operation-related costs) for the windfarm. The second scenario assumes, that the owner of the electrolyser buys the electricity from the owner of the wind farm. In this case the costs for the electricity would be demand-related costs, as it would only be payed when the electrolyser is in operation

Due to the fact this project only analyses the costs of hydrogen production and revenues are extremely dependent on the use of the hydrogen, potential revenues from hydrogen sales are not taken into account.

The levelized cost of hydrogen (LCOH) is calculated using the equation

$$LCOH = \frac{total\ annuity\ \left[\frac{\$}{a}\right]}{produced\ hydrogen\ \left[\frac{kg}{a}\right]}\ \left[\frac{\$}{kg}\right]$$

The produced hydrogen per year is calculated using the electrical power of the electrolyser, the system energy consumption per kg hydrogen (efficiency) and the full load hours.

$$produced\ hydrogen = \frac{electrical\ power\ [kW] x\ FLH\ \left[\frac{h}{a}\right]}{efficiency\ \left[\frac{kWh}{kg}\right]}\ \left[\frac{kg}{a}\right]$$

6.1.1 Description of the calculation of hydrogen production costs

The hydrogen production costs consist of the individual costs for the following items/components:

- Electricity generation
- Electricity Grid
- Electrolyser
- Water supply
- Transport of hydrogen

The costs for these items/components depend on the chosen scenario and are calculated for each variation:

- Location of electrolyser
- Location of wind farm
- Location of consumer
- Transport technology

The CAPEX and OPEX for each item/component is calculated separately using the annuity method ($/year).These annual costs are then related to the annual produced hydrogen quantity (kg/year) to get to the costs per kg of produced hydrogen ($/kg).

These costs per item are then summed up:
Hydrogen production cost ($/kg) =
Annual cost of electricity generation / annual produced hydrogen quantity
\+ Annual costs of electricity grid / annual produced hydrogen quantity
\+ Annual costs of electrolyser / annual produced hydrogen quantity
\+ Annual costs of transport of hydrogen / annual produced hydrogen quantity
\+ Annual costs of water supply / annual produced hydrogen quantity

By doing the calculation in this way (step by step), the individual cost components can be compared and analysed.

The annually produced hydrogen quantity is determined as follows:

- The hydrogen production [kg/year] results from electrolyser capacity * full load hours * efficiency of the electrolyser.
- The full load hours of the electrolyser depend on the power supply taking into account the location of the wind farm, respectively the location of the hybrid power plant and the wind and solar resource conditions at those locations.

A separate, additional sensitivity analysis will provide the sensitivity of the parameter in the table. These calculations are carried out for some selected scenarios.

6.2 LCOE calculation and hybrid system configuration

Designing an electrolyser plant powered by renewable energies to produce green hydrogen needs to take into account calculations of energy supply, energy costs and operational costs to find the optimal configuration. In this chapter, an approach for the calculation of the LCOE for four sites in Río Negro is presented as basis for further analysis and decision-making. The focus is on the economic efficiency of a combined electricity supply by a hybrid power plant (wind and solar).

The result of this approach is a configuration of a combined wind and solar power plant to feed the electrolyser leading to the lowest LCOH although LCOE might be higher.

6.2.1 Methodology

To determine the economic optimal share of solar and wind energy to supply a electrolyser plant at the four defined locations in Río Negro (Cerro Policía, El Solito, Laguna de la Retención, and Pomona), wind and solar data, economic assumptions and a formula to calculate the LCOE are required. Wind and solar time series were provided by the open energy system database project renewables.ninja (Pfenninger und Staffell 2016), economic assumptions were taken from (Armijo und Philibert 2020), and the LCOE formula was developed in accordance with the guidelines (Verein deutscher Ingenieure VDI 2012a, 2012b).

Firstly, the hourly time series data sets for Cerro Policía, El Solito, Laguna de la Retención and Pomona were generated for wind and solar energy with specific settings. To determine the wind production data a Vestas V112 3000 with a hub height of 112 metres is used as the referenced wind turbine. To determine the solar data an angle of 40°, no tracking and system losses of 10 % were chosen.

Table 19: Coordinates of the hybrid power plant sites

	lat	lon
Cerro Policía	-39.370912	-68.458938
El Solito	-39.933766	-65.194886
Laguna de la Retención	-40.8541944	-65.4655556
Pomona	-39.598538	-65.829253

The hourly wind and solar data from renewables.ninja was used to create factors (hereinafter referred to as ‘part load factors’) for the power generated per hour and per unit of installed capacity. For example: the power generated by a wind turbine with a capacity of 1 MW between 0:00 and 1:00 on January 1st was 870 kWh, the part load factor for this time interval is 0.87.

In order to determine the optimal ratio of installed wind and PV power, calculations are carried out with different installed capacities of wind and PV power. The PV power varies between 35-75% of the electrolysis power, additionally 0% and 5% were analysed to show the lowest possible LCOE. For wind the installed power is considered between 90 and 150% of the electrolysis power.

The levelised cost of electricity (LCOE) were calculated by using the following formula:

$$LCOE = \frac{I_0 * a + A_1 * a * b}{M_{1,el}}$$ with LCOE in US$/MWh

I_0 Investment costs in USD
A_1 Overall annual costs in USD in year 1
a Annuity factor (calculated from interest rate and observation period)
b Cash value factor (calculated from interest rate and observation period and cost escalation rate)
$M_{1,el}$ Amount of generated electrical power in MWh in year 1

The following assumptions were made for calculating the LCOE:

Table 20: Parameters for LCOE calculation

Parameter	Value	Reference
CAPEX solar [USD/kW]	740	(Armijo und Philibert 2020)
CAPEX wind [USD/kW]	1300	(Armijo und Philibert 2020)
OPEX solar [USD/(kW*a)]	12.58	(Armijo und Philibert 2020)
OPEX wind [USD/(kW*a)]	26	(Armijo und Philibert 2020)
Observation period [a]	25	(Armijo und Philibert 2020)
Interest rate	0.08	decided by the project team
Cost escalation rate	0.017	decided by the project team

6.2.2 Results of wind farm analysis

The results of the analysis of the provided data are shown in Table 21. These are used as input parameters for the LCOH calculation.

Table 21: Full load hours of wind farm, PV plant and electrolysis

	FLH wind (provided by Rio Negro)	FLH Wind (Pfenninger und Staffell 2016)	FLH PV (Pfenninger und Staffell 2016)	FLH Ely (wind only)
Cerro Policía	4380	4420	1794	4380
Pomona	3793	4310	1729	4095[1]
El Solito	not provided	4378	1711	4159[2]
Laguna de la Retención	4152	4381	1708	4152

[1] Due to major deviation regarding FLH of wind in Pomona, calculations have been done with 95% of wind FLH from Pfenninger und Staffell 2016.
[2] 95% of wind FLH from Pfenninger und Staffell 2016.

6.2.3 Results of hybrid plant configuration

Due to only minor differences between the four locations, all following figures provide exemplarily data for Cerro Policía.

An example for the part load factors of Wind and PV as well as resulting load of the electrolyser is shown in Figure 32 and Figure 33. Both figures visualise the effect of wind and solar power combined on the electrolyser operating hours.

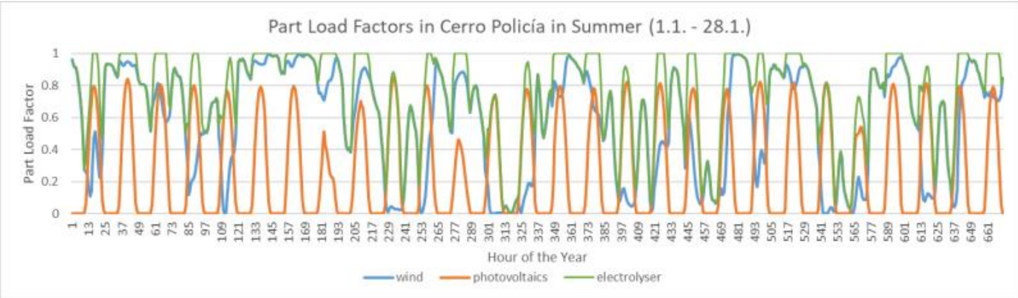

Figure 32: Part Load Factors of Wind, Photovoltaics and Electrolyser in Cerro Policía in the Argentinean Summer

An additional PV plant supports the energy supply for the electrolyser during days with low wind speeds and leads to an improved, more consistent hydrogen production.

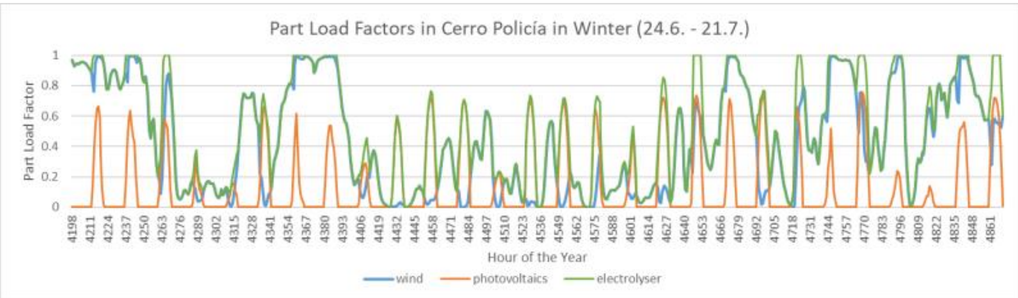

Figure 33: Part Load Factors of Wind, Photovoltaics and Electrolyser in Cerro Policía in the Argentinean Winter

Based on the analysis of the time series for every combination of wind farm size and solar plant size, the full load hours of the electrolyser were calculated.

Figure 34 shows the effect of different installed capacities on the electrolyser's full load hours. An increase in wind capacity as well as in photovoltaics capacity lead to an increase of electrolyser FLH (colour shift from red for lower values to green for higher values). Therefore, the highest number of FLHs is with the highest installed capacity.

		Wind [MW]												
		90	95	100	105	110	115	120	125	130	135	140	145	150
PV[MW]	0	3,978	4,199	4,420	4,620	4,792	4,944	5,081	5,204	5,316	5,417	5,509	5,592	5,670
	5	4,068	4,289	4,506	4,699	4,865	5,014	5,148	5,269	5,379	5,478	5,568	5,651	5,728
	35	4,567	4,760	4,944	5,113	5,261	5,395	5,517	5,629	5,730	5,821	5,904	5,980	6,050
	40	4,638	4,827	5,009	5,175	5,322	5,454	5,574	5,684	5,784	5,874	5,956	6,031	6,100
	45	4,707	4,892	5,071	5,235	5,380	5,511	5,630	5,739	5,837	5,926	6,007	6,080	6,149
	50	4,773	4,956	5,132	5,294	5,438	5,567	5,685	5,792	5,889	5,977	6,056	6,129	6,196
	55	4,838	5,017	5,192	5,352	5,494	5,621	5,738	5,843	5,939	6,026	6,104	6,176	6,243
	60	4,900	5,077	5,250	5,408	5,548	5,674	5,789	5,894	5,988	6,074	6,152	6,223	6,289
	65	4,960	5,136	5,306	5,463	5,601	5,726	5,839	5,943	6,036	6,121	6,198	6,268	6,333
	70	5,019	5,192	5,361	5,515	5,652	5,776	5,888	5,990	6,083	6,167	6,244	6,313	6,377
	75	5,076	5,247	5,413	5,567	5,702	5,824	5,936	6,037	6,129	6,212	6,288	6,356	6,420

Figure 34: resulting full load hours electrolyser plant in Cerro Policía

Cost analysis and results of hydrogen production costs

Considering the calculation of the levelised cost of hydrogen (LCOH), the optimal ratio of installed wind and solar power is different in contrast to the ratio for the lowest LCOE. Whereas the lowest LCOE is, as expected, with wind power only, the increasing FLH of the electrolyser are responsible for the advantageousness of an increased share of solar power in case of calculating LCOHs.

		Wind [MW]												
		90	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**	**140**	**145**	**150**
PV[MW]	**0**	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35	34,35
	5	34,63	34,61	34,60	34,59	34,58	34,57	34,56	34,55	34,54	34,54	34,53	34,53	34,52
	35	36,04	35,97	35,90	35,83	35,77	35,72	35,67	35,62	35,58	35,53	35,50	35,46	35,43
	40	36,25	36,16	36,09	36,01	35,95	35,89	35,83	35,78	35,73	35,69	35,64	35,60	35,57
	45	36,45	36,35	36,27	36,19	36,12	36,05	35,99	35,94	35,88	35,83	35,79	35,74	35,70
	50	36,64	36,54	36,45	36,36	36,29	36,21	36,15	36,09	36,03	35,97	35,92	35,88	35,83
	55	36,82	36,71	36,62	36,53	36,45	36,37	36,30	36,23	36,17	36,11	36,06	36,01	35,96
	60	37,00	36,88	36,78	36,69	36,60	36,52	36,45	36,38	36,31	36,25	36,19	36,14	36,09
	65	37,17	37,05	36,94	36,84	36,75	36,67	36,59	36,52	36,45	36,38	36,32	36,26	36,21
	70	37,33	37,21	37,10	37,00	36,90	36,81	36,73	36,65	36,58	36,51	36,45	36,39	36,33
	75	37,49	37,36	37,25	37,14	37,04	36,95	36,86	36,78	36,71	36,64	36,57	36,51	36,45

Figure 35: LCOE of Hybrid plants in Cerro Policía [$/MWh]

		Wind [MW]												
		90	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**	**140**	**145**	**150**
PV[MW]	**0**	5,0440	4,8681	4,7098	4,5867	4,5013	4,4388	4,3931	4,3612	4,3400	4,3285	4,3249	4,3275	4,3343
	5	4,9839	4,8147	4,6655	4,5545	4,4758	4,4180	4,3763	4,3469	4,3280	4,3182	4,3159	4,3194	4,3270
	35	4,7121	4,5999	4,5041	4,4294	4,3757	4,3367	4,3090	4,2907	4,2807	4,2780	4,2816	4,2902	4,3025
	40	4,6841	4,5787	4,4879	4,4164	4,3653	4,3283	4,3023	4,2853	4,2763	4,2746	4,2791	4,2884	4,3014
	45	4,6599	4,5601	4,4735	4,4050	4,3563	4,3211	4,2966	4,2808	4,2730	4,2722	4,2775	4,2876	4,3012
	50	4,6385	4,5439	4,4607	4,3951	4,3485	4,3151	4,2919	4,2774	4,2707	4,2708	4,2770	4,2876	4,3017
	55	4,6199	4,5295	4,4496	4,3865	4,3420	4,3103	4,2885	4,2751	4,2694	4,2705	4,2772	4,2883	4,3028
	60	4,6036	4,5169	4,4399	4,3794	4,3369	4,3066	4,2861	4,2739	$\boxed{4,2691}$	4,2709	4,2781	4,2896	4,3045
	65	4,5894	4,5058	4,4320	4,3738	4,3331	4,3042	4,2849	4,2737	4,2697	4,2719	4,2795	4,2915	4,3068
	70	4,5770	4,4968	4,4257	4,3697	4,3305	4,3028	4,2846	4,2743	4,2709	4,2736	4,2816	4,2941	4,3097
	75	4,5667	4,4896	4,4209	4,3667	4,3289	4,3025	4,2852	4,2756	4,2728	4,2760	4,2845	4,2974	4,3133

Figure 36: generic LCOH of an electrolyser in Pomona fed by a hybrid plant in Cerro Policía [$/kg]

The method of calculating LCOEs and LCOHs shown here as an example for a hybrid power plant in Cerro Policía was carried out for all combinations of hybrid power plant site and electrolysis site. The following Table 22 shows the resulting hybrid system configurations for every combination of electricity source and location of electrolyser.

Table 22: Hybrid system configuration and resulting FLHs of the electrolyser

Location of Hybrid plant		**Pomona**	**El Solito**	**Laguna de la Retención**
Cerro Policía	Configuration	130 Wind 60 PV	135 Wind 70 PV	135 Wind 70 PV
	resulting FLHs of the electrolyser	5988	6167	6167
at the site of the electrolyser (Po, ElS, LR)	Configuration	135 Wind 60 PV	135 Wind 60 PV	135 Wind 70 PV
	resulting FLHs of the electrolyser	6020	6158	6235

Actually the optimisation of the hybrid plant must be carried out for each of the 78 scenarios, as costs for transport and optional downstream processes vary. Every change in cost data can cause shifts in the configuration of the optimal hybrid plant. The values presented in this chapter are calculated with average transport costs and therefore not identical with the results of the detailed LCOH calculations in the following chapter

.

6.3 Assumptions and calculation parameter

The technical and economical parameters used to perform the LCOH calculations are shown in Table 23.

Table 23: Calculation parameter

Parameter	Domestic scenario	Export scenario	Unit
Capacity of electrolyser P	100	500	MW_{el}
Efficiency of electrolyser η	67.3	68.2	%
Lifetime of stack	80,000	90,000	h
Interest rate i	8	8	%
Cost escalation rate r	1.7	1.7	%
Observation period	25	25	years

The basis for the cost analysis are the assumptions on CAPEX and OPEX presented in Table 24.

Table 24: CAPEX and OPEX of different cost items

Component	CAPEX	OPEX	Comment	Source
Wind farm	1300 $/kW	26 $/(kW*a)		(Armijo und Philibert 2020)
PV	740 $/kW	12.5 $/kW*a		(Armijo und Philibert 2020)
Electricity grid 500 kV	735,540 $/km	2% of CAPEX		(Claudi 2015)
Electricity grid 132 kV	245,180 $/km	2% of CAPEX		(Claudi 2015)
Substation	245 $/kW	2% of CAPEX		(Dambeck et al. 2020b)
Electrolyser domestic scenario	834 $/kW	15.27 $/kW*a	2025; 100 MW	cost curve IEE
Electrolyser export scenario	724 $/kW	11.94 $/(kW*a)	2030; 500 MW	cost curve IEE
Infrastructure & water	110 $/kW	1% of CAPEX	water supply, etc.	IEE analysis
Pipeline export scenarios	500,000 $/km	2% of CAPEX		(Reuß et al. 2017)
Pipeline domestic scenarios	450,000 $/km	2% of CAPEX		(Reuß et al. 2017)
Truck	185,000 $	12% of CAPEX	500 km/d	(International Energy Agency (IEA) 2019a)
Trailer	650,000 $	2% of CAPEX	670 kg/trailer	(International Energy Agency (IEA) 2019a)
GH2 storage	41,74 $/kg	3% of CAPEX		(International Energy Agency (IEA) 2019a)

liquefaction wind	196,114,000 $	3% of CAPEX		(Reuß et al. 2017)
liquefaction hybrid	232,921,000 $	3% of CAPEX		(Reuß et al. 2017)
LH2 storage & terminal	114,928,125 $	3% of CAPEX		(International Energy Agency (IEA) 2019a)
Ship	104,201,500 $	3% of CAPEX	Capacity: 2500 t LH_2	(International Energy Agency (IEA) 2019a)

Analyzing the provided document "Localizaciones V2" results in the lengths of the new high-voltage lines to be erected.

Table 25: Distances for electricity transport (additionally erected transmission line)

	Distance
Cerro Policía --> Pomona	9,77 km
Cerro Policía --> El Solito	75 km
Cerro Policía --> Laguna de la Retención	9,53 km
Cerro Policía --> Chocón	5 km

The distances for hydrogen transport as basis for transport cost calculations are summarized in the table below. Additional graphics explaining the distances can be found in the Annex.

Table 26: Distances for hydrogen transport in domestic scenarios

Location of electrolyser	**destination**	**distance pipeline**	**distance truck**
Pomona	Cipoletti	200 km	262 km
Pomona	Bahia Blanca	325 km	360 km
El Solito	Cipoletti	265 km	325 km
El Solito	Bahia Blanca	285 km	386 km
Laguna de la Retención	Cipoletti	340 km	450 km
Laguna de la Retención	Bahia Blanca	290 km	375 km
Chocón	Refinery in Plaza Huincul	55 km	90 km
Chocón	Refinery in Bahía Blanca	560 km	622 km
Chocón	Mobility in Cipolletti	75 km	90 km

The distances for hydrogen transport from the hydrogen factory to the port via pipeline are presented in Table 27.

Table 27: Distance for hydrogen transport to the port in export scenarios

Location of electrolyser	**destination**	**distance pipeline**
Pomona	Port San Antonio Oeste	160 km
El Solito	Port San Antonio Oeste	100 km
Laguna de la Retención	Port San Antonio Oeste	30 km

The assumptions on the efficiency increase of electrolysis over time due to learning effects is shown in Figure 37.

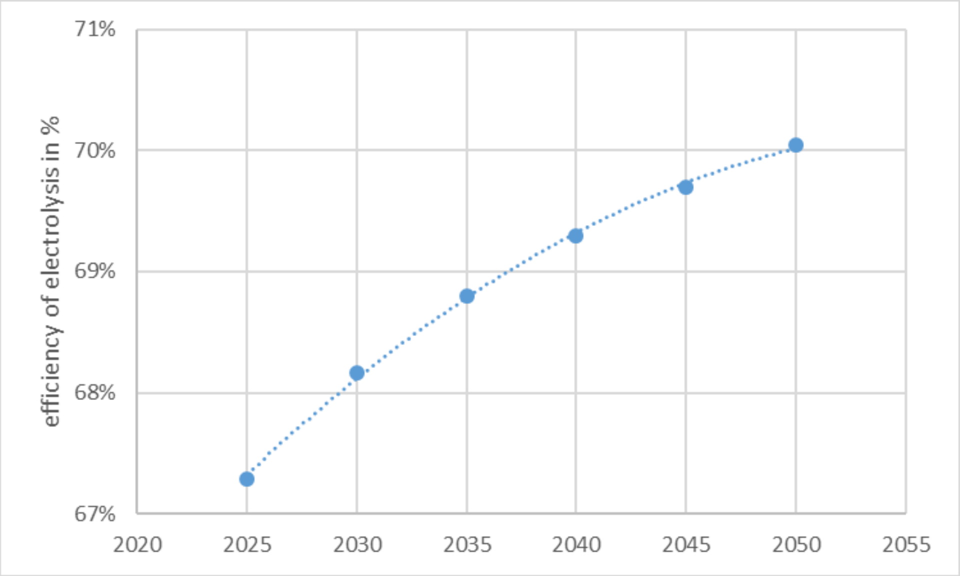

Figure 37: Efficiency of electrolysis

The assumptions on cost reduction over time are presented in Figure 38 and Figure 39.

The cost curves were generated within IEE taking into account the following sources:

- (Bertuccioli et al. 2014)
- (Smolinka et al. 2018b)
- (Bazzanella und Ausfelder 2017)
- (International Energy Agency (IEA) 2019a)
- (van 't Noordende und Ripson 2020)
- (Hydrogen Council 2020)

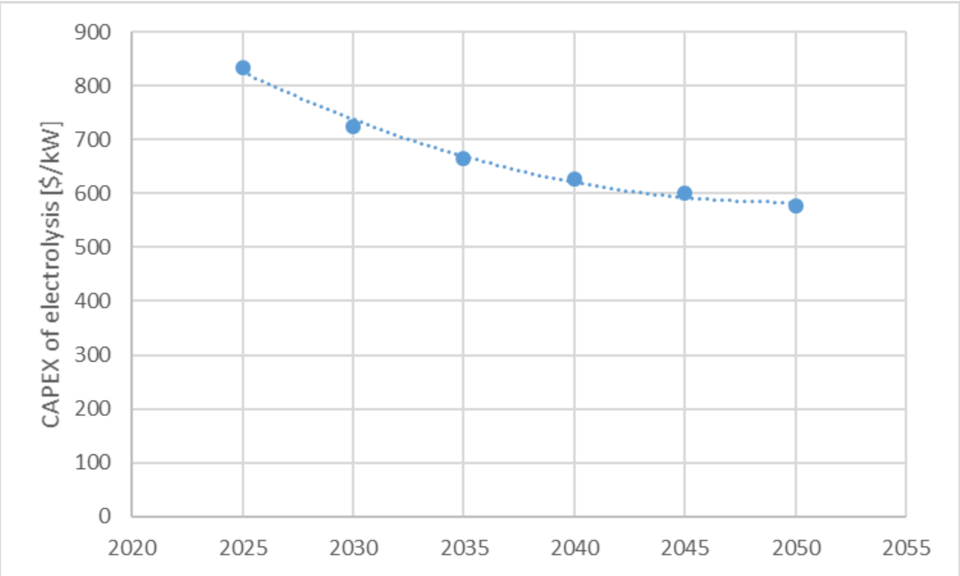

Figure 38: CAPEX of electrolysis

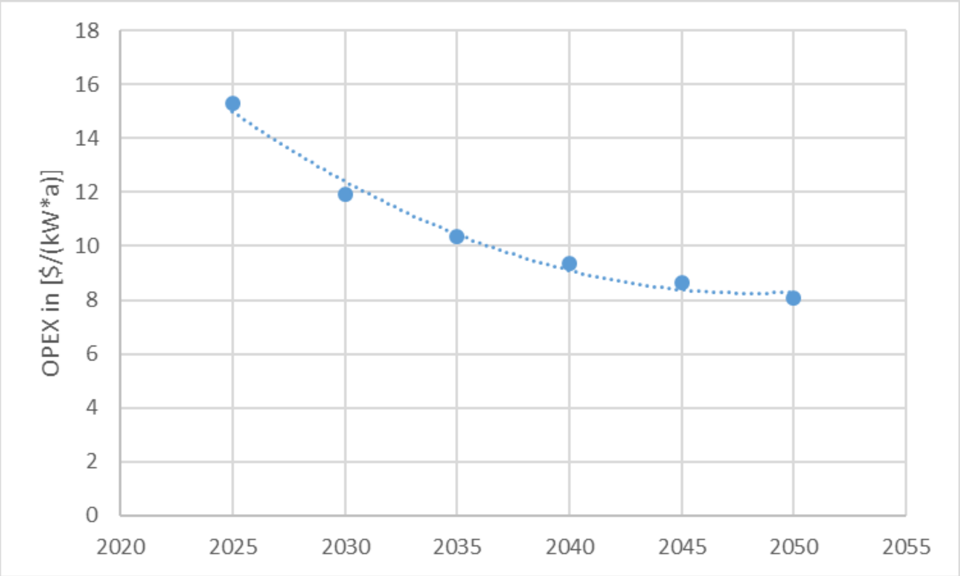

Figure 39: OPEX of electrolysis

6.4 Results of LCOH calculations

In the following 4 figures, the results of the LCOH calculation are summarized graphically for each electrolyser location. The results of the LCOH calculation are also included in a separate Excel table.

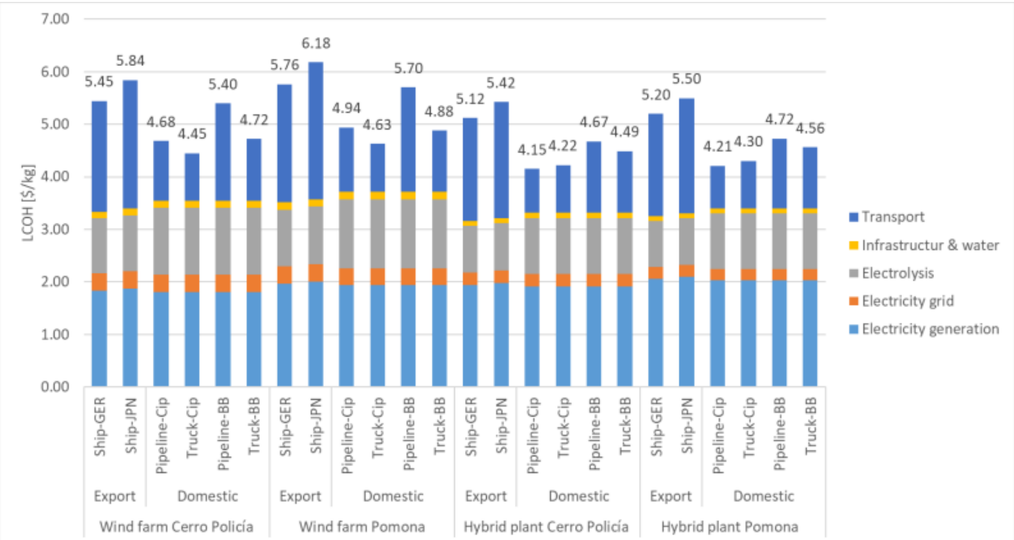

Figure 40 LCOH in $/kg for all scenarios for the electrolyser location Pomona.

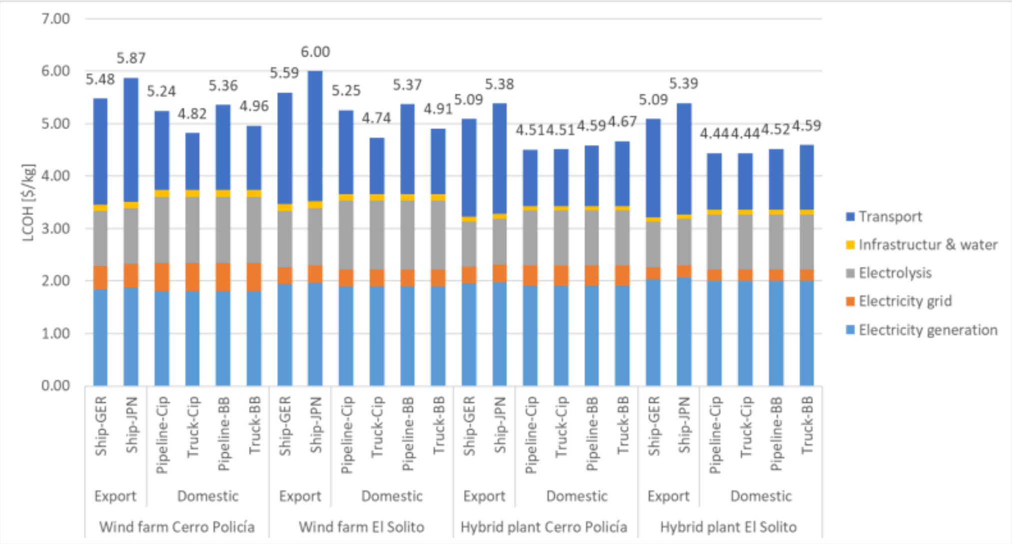

Figure 41: LCOH in $/kg for all scenarios for the electrolyser location El Solito.

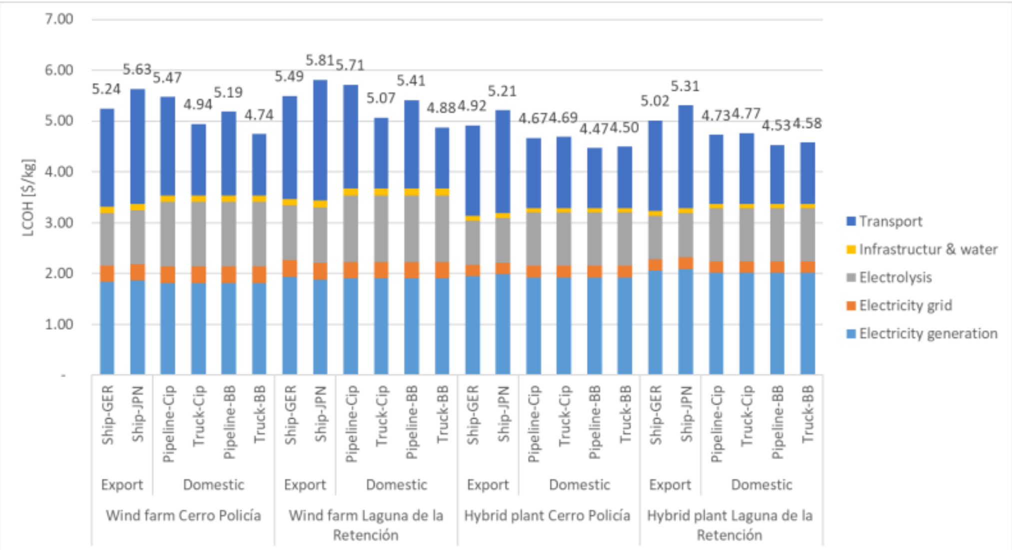

Figure 42: LCOH in $/kg for all scenarios for the electrolyser location Laguna de la Retención.

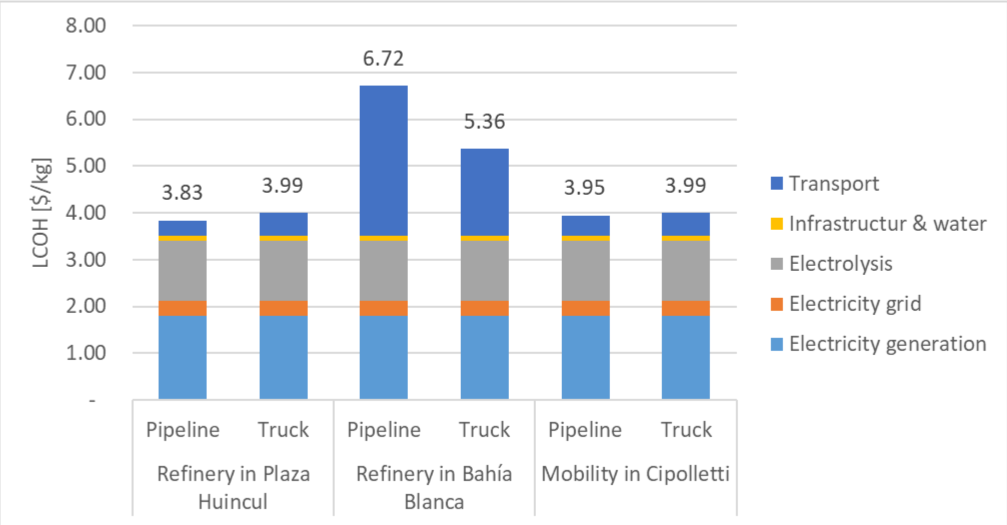

Figure 43: LCOH in $/kg for all scenarios for the electrolyser location El Chocón.

The results show that the costs for producing hydrogen including transport are between 4.15 $/kg and 6.18 $/kg for Pomona, between 4.44 $/kg and 6.00 $/kg for El Solito, between 4.47 $/kg and 5.81 $/kg for Laguna de la Retención, and between 3.83 $/kg and 6.72 $/kg for El Chocón. The following tables summarize the minima, maxima and average values for both the ecport and the domestic scenarios.

El Chocón has the lowest LCOH (less than 4 $/kg). The LCOH are so low because of the low electricity generation costs and especially when the hydrogen consumer is close to the electrolyser location. Due to the distance to Bahia Blanca, the highest LCOH of all scenarios is also determined for El Chocón (for Cho-WF/CP-domestic-100-pipeline-BB).

Table 28: Minima, maxima and average values for all electrolyser locations both the export and the domestic scenarios.

Costs in $/kg	Pomona	El Solito	Laguna de la Retención	Chocón
Average all scenarios	4.97	5.03	5.04	4.64
Minimum all scenarios	4.15	4.44	4.47	3.83
Maximum all scenarios	6.18	6.00	5.81	6.72

Table 29: Minima, maxima and average values for all electrolyser locations for the export scenarios

Costs in $/kg	Pomona	El Solito	Laguna de la Retención	Chocón
Average export scenarios	5.56	5.49	5.33	
Minimum export scenarios	5.12	5.09	4.92	
Maximum export scenarios	6.18	6.00	5.81	

Table 30: Minima, maxima and average values for all electrolyser location for the domestic scenarios.

Costs in $/kg	Pomona	El Solito	Laguna de la Retención	Chocón
Average domestic scenarios	4.67	4.82	4.91	4.64
Minimum domestic scenarios	4.15	4.44	4.53	3.83
Maximum domestic scenarios	5.70	5.37	5.71	6.72

The costs are higher for the export scenarios than for the domestic scenarios for all locations. The difference is most evident at Pomona, where the costs for the transport scenarios are almost 20% above the domestic scenarios.

Although the pure costs for the production of hydrogen in the export scenarios are slightly lower than in the domestic scenarios, the transport costs are significantly higher in the export scenarios. Using the example of Pomona, the following graphic shows the proportions of hydrogen generation (sum of the cost parts from electricity generation, power grid, electrolyser, and infrastructure) and transport.

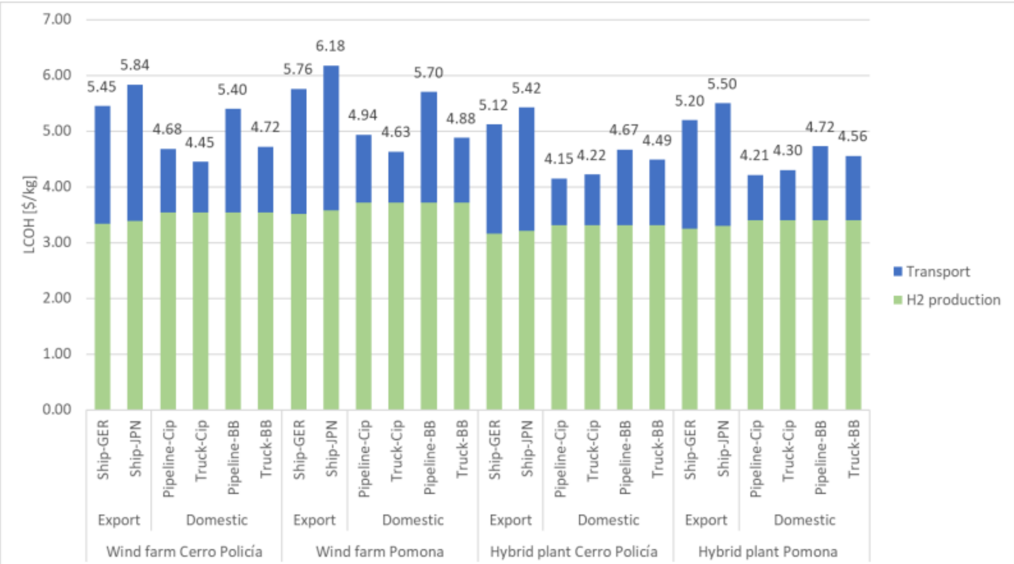

Figure 44: LCOH in $/kg for all scenarios for the electrolyser location Pomona

The following graphic summarizes the export scenarios for Pomona, El Solito and Laguna de la Retención. The costs vary between 4.98 and 6.18 $/kg. The costs for hydrogen transported to Germany as a consumer country are always slightly lower than for Japan because the distance and travel time are shorter and thus fewer ships are required.

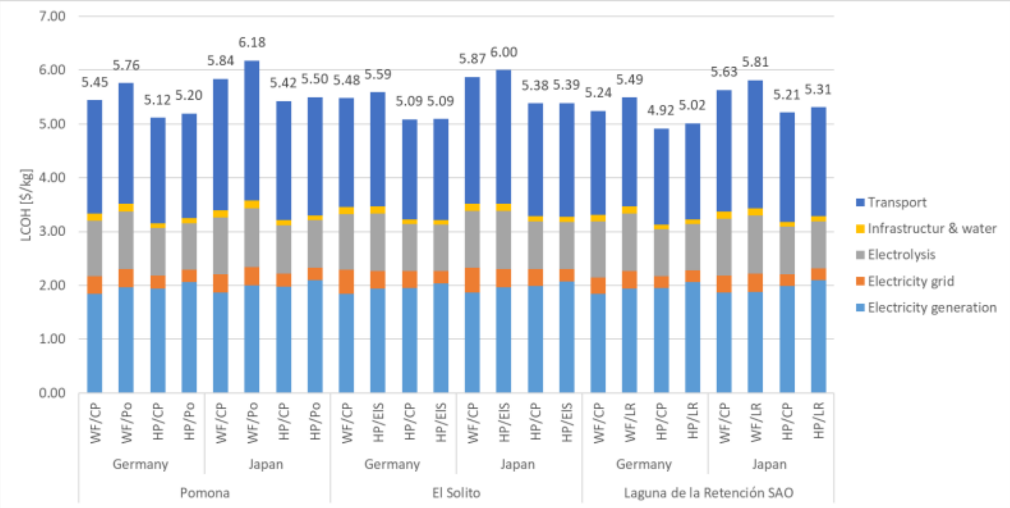

Figure 45: LCOH in $/kg for all export scenarios for all electrolyser location for Pomona, El Solito and Laguna de la Retención

The hydrogen costs (in the export scenarios) are lower in the scenarios with hybrid systems than with wind farms alone. Although the costs for generating electricity are higher with hybrid systems, significantly more full-load hours of electrolyser are achieved so that more hydrogen can be produced. Thus, the annual costs are distributed over a higher amount of hydrogen and the hydrogen production costs decrease. See also chapter 6.2.

The following graphics show the same results but in a different breakdown. One graphic shows all scenarios for the wind farm in Cerro Policía (for power generation) and the second all scenarios for the hybrid system in Cerro Policía (for power generation).

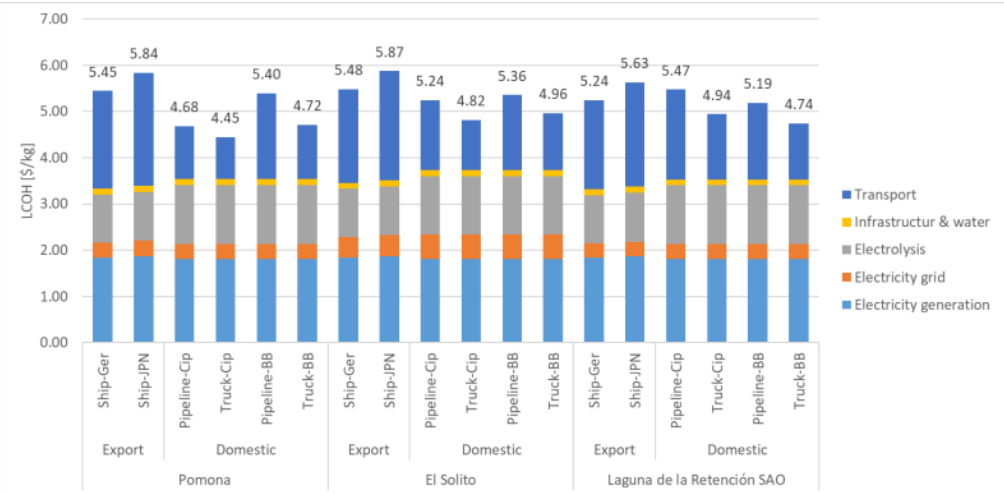

Figure 46 LCOH in $/kg for all scenarios with wind farm in Cerro Policía.

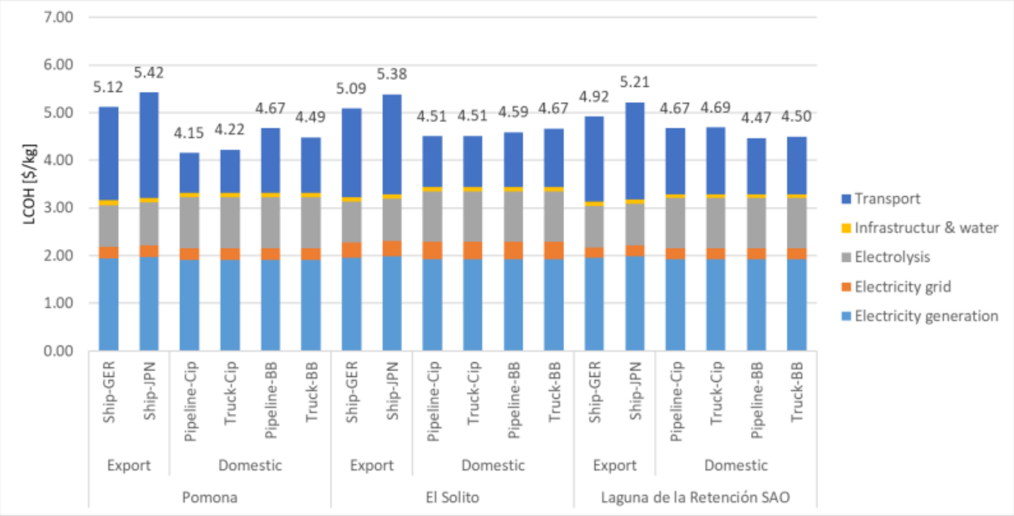

Figure 47 LCOH in $/kg for all scenarios with hybrid plant in Cerro Policía

In the domestic scenarios, the costs in the scenarios with hybrid systems than with wind farms alone differ between truck transport and pipeline transport. With truck transport in the case of domestic scenarios, lower LCOH are achieved if only a wind farm in Cerro Policía is used. On the other hand, lower LCOH are achieved with pipeline transport if a hybrid system is used in Cerro Policía.

There is an explanation that different hydrogen quantities arise at the same electrolyser location in the respective case of supply via the wind farm or the hybrid system. These leads to the fact that with hybrid plants and respectively higher hydrogen quantities the pipeline is more cost-effective than the trucks and, in contrast, with smaller quantities the truck is cheaper.

In the following, all scenario with truck transport are summarized in one graphic and all scenarios with pipeline transport are summarized in another graphic.

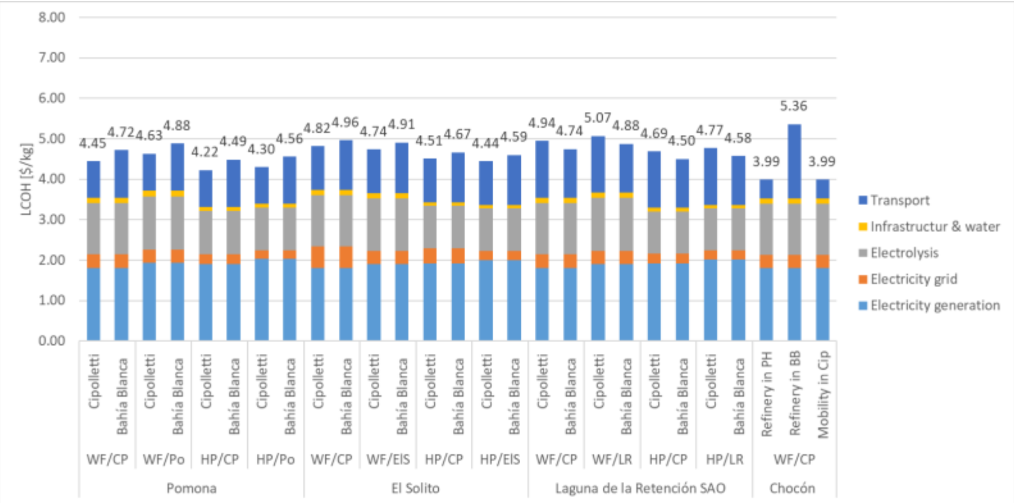

Figure 48 LCOH in $/kg for all scenarios with truck and trailer transport

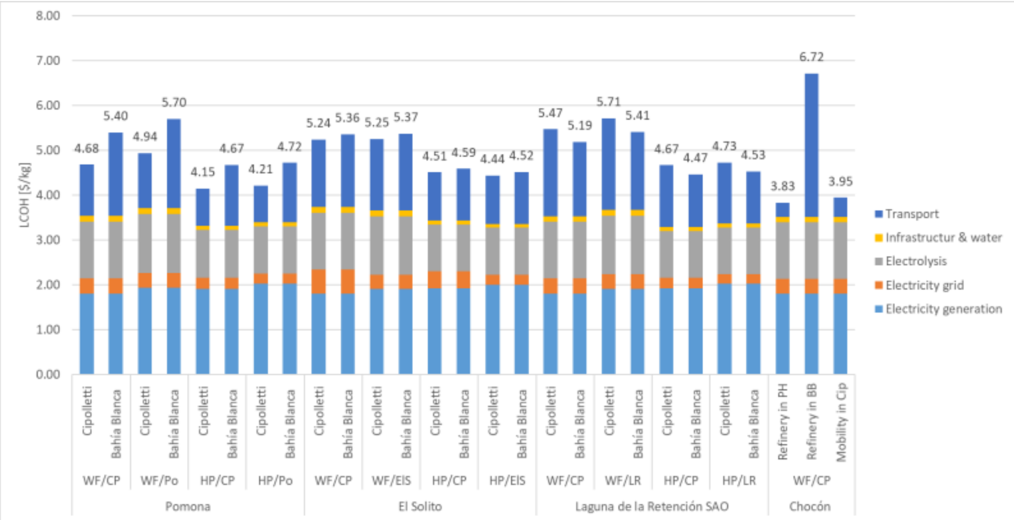

Figure 49: LCOH in $/kg for all scenarios with pipeline transport

These results show that in most scenarios, truck transport is cheaper than pipeline transport. The results also show, however, that the choice of the domestic consumer location has a significant influence due to the resulting different distances between the electrolyser and the consumer. Therefore, it is always necessary to evaluate for each electrolysis location

- which hydrogen quantities are generated (this depends on the electrolyser capacity and the electrolyser full load hours which depends on the selected electricity generation), and
- where the location of the consumer is, and therefore how big the distance is between consumer and electrolyser.

Two selected scenarios each for domestic hydrogen use and export of hydrogen are described in the chapter 6.6.

6.5 Sensitivity analysis

A sensitivity analysis was carried out. Therefore the electrolyser location Pomona was used as an example. The parameters mentioned in the table below were varied. The results are shown in the following figures.

Table 31: Parameter variation for sensitivity analysis

Parameter	Unit	Mininum	Reference value	Maximum
Interest rate	%	5	8	12
Cost escalation rate	%	1,45	1,7	2, 5, and 10
Lifetime of stack	hours	- 30,000	80,000 / 90,000	+ 30,000
CAPEX electrolyser	$/kW	75% of reference	depending on scenario	125% of reference
CAPEX all components	$/kW	75% of reference	depending on scenario	125% of reference
OPEX all components	$/kW*a	75% of reference	depending on scenario	125% of reference
Full load hours of electricity generation	hours/year	80% of reference	depending on scenario	120% of reference

The following two figures show the results of the sensitivity analysis for variations of the interest rate and the cost escalation rate.

If the interest rate is increased from 8 to 12%, the hydrogen production costs increase by 0.97 to 1.75 US$/kg resp. 22 to 29%. If the interest rate is reduced from 8 to 5%, the hydrogen production costs drop by 0.66 to 1.20 US$/kg resp. 15 to 20%.

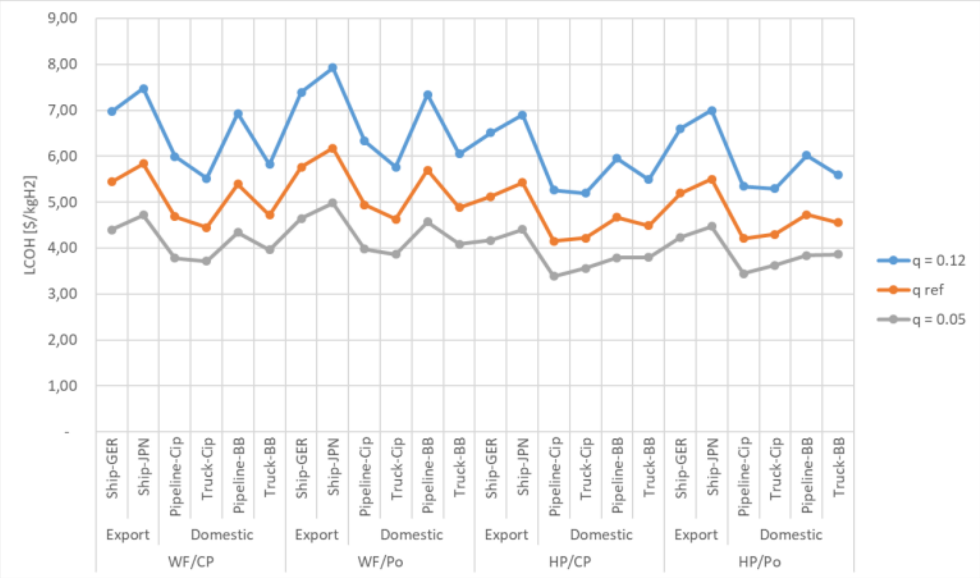

Figure 50: Results of sensitivity analysis for electrolyser location Pomona – absolute values of LCOH for different interest rates.

If the cost escalation rate is increased from 1.7 to 2%, then the hydrogen production costs only rise by a few cents per kg resp. around 1%. However, if the cost escalation rate is increased from 1.7 to 10%, then the hydrogen production costs increase significantly by 1.52 to 2.67 US$/kg resp. 35 to 51%. If the cost escalation rate is reduced from 1.7 to 1.45%, the hydrogen production costs only decrease by a few cents per kg resp. around 1%.

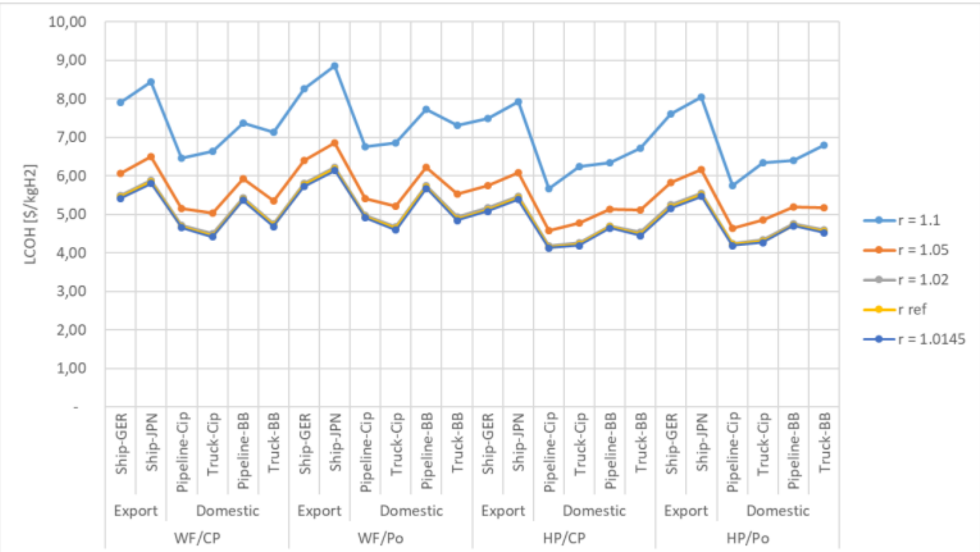

Figure 51: Results of sensitivity analysis for electrolyser location Pomona – absolute values of LCOH for different cost escalation rate.

The following Figure 52 shows the results of the sensitivity analysis for variation of the stack lifetime.

If the stack lifetime is increased by 30,000 hours the hydrogen production costs decrease by 0.09 to 0.18 US$/kg resp. 1 to 4%. If the stack lifetime is reduced by 30,000 hours, the hydrogen production costs increase by 0.21 to 0.35 US$/kg resp. 4 to 9%.

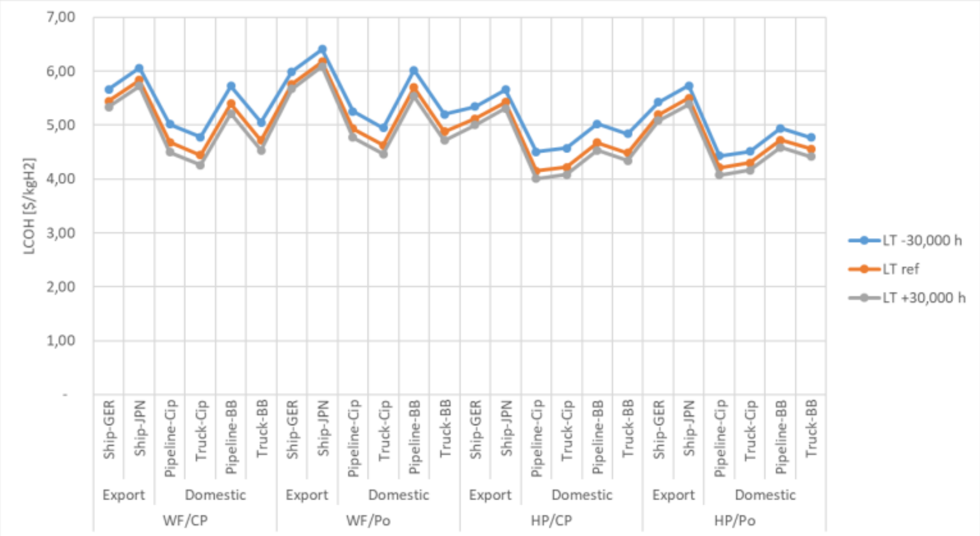

Figure 52: Results of sensitivity analysis for electrolyser location Pomona – LCOH for different stack lifetimes.

The following three figures show the results of the sensitivity analysis for variation of the electrolyser CAPEX, the CAPEX of all components together, and the OPEX of all components together.

If the electrolyser CAPEX is increased by 25%, the hydrogen production costs increase by 0.19 to 0.27 US$/kg resp. 4 to 6 %. If the electrolyser CAPEX is reduced by 25%, the hydrogen production costs decrease by 0.19 to 0.27 US$/kg resp. 4 to 6 %.

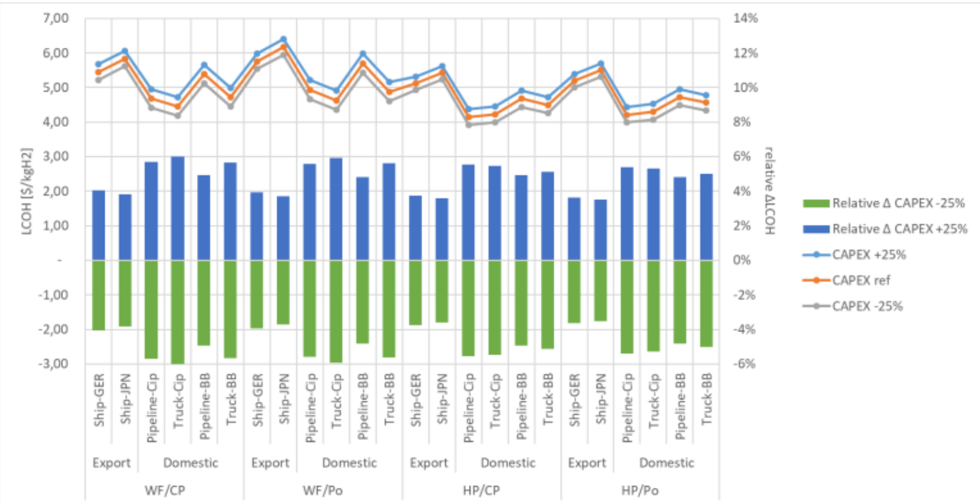

Figure 53: Results of sensitivity analysis for electrolyser location Pomona – absolute values and relative changes of LCOH for different electrolyser CAPEX.

If the CAPEX of all components together (electricity production, grid connection, electrolyser, infrastructure, and transport) is increased by 25%, the hydrogen production costs increase by 0.91 to 1.39 US$/kg resp. 22%. If the CAPEX of all components together is reduced by 25%, the hydrogen production costs drop by 0.91 to 1.39 US$/kg resp. 22%.

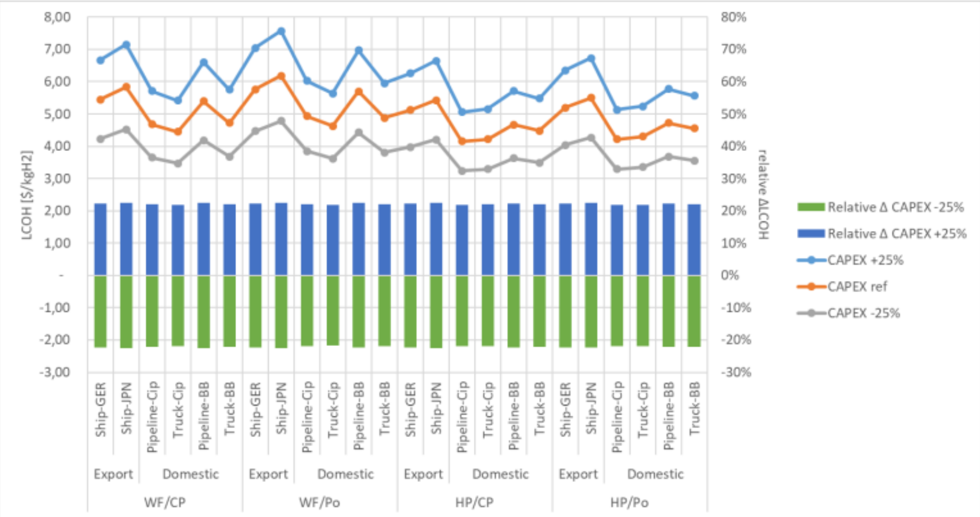

Figure 54: Results of sensitivity analysis for electrolyser location Pomona – absolute values and relative changes of LCOH for different CAPEX of all components together.

If the OPEX of all components together (electricity production, grid connection, electrolyser, infrastructure, and transport) is increased by 25%, the hydrogen production costs increase by 0.19 to 0.42 US$/kg resp. 4 to 7%. If the OPEX of all components together is reduced by 25%, the hydrogen production costs decrease by 0.19 to 0.42 US$/kg resp. 4 to 7%.

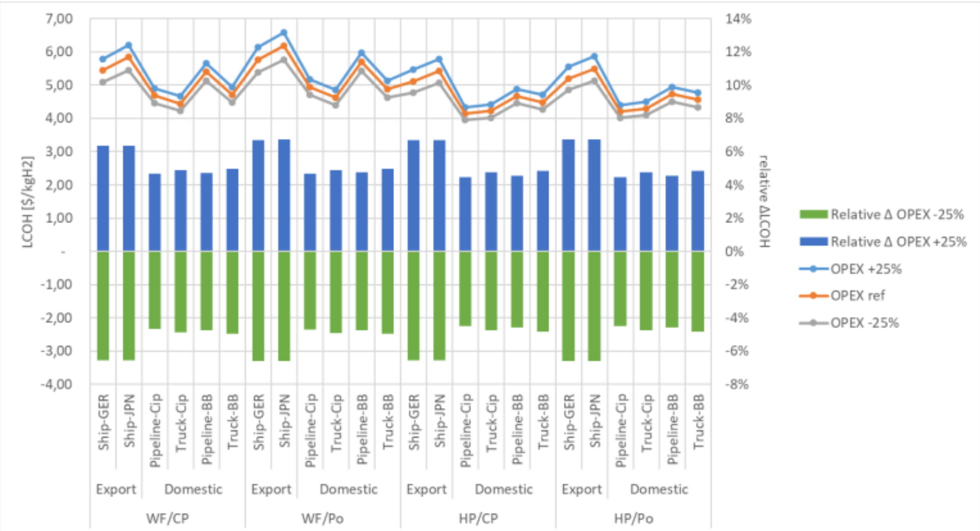

Figure 55: Results of sensitivity analysis for electrolyser location Pomona – absolute values and relative changes of LCOH for different OPEX of all components together.

The following two figures show the results of the sensitivity analysis for variation of the full load hours of the electricity generation plants and thus in resulting variation of the full load hours of the electrolyser. For this calculation, it is assumed that the full load hours of the wind farm in Cerro Policia or Pomona and of the hybrid plant in Cerro Policia or Pomona are 20 % higher or lower than determined in chapter 6.2.

The variation of the full load hours of the electricity generation plant results in changed electricity production costs (LCOE) which also influences the hydrogen production costs.

If the full load hours of the electricity generation plant are increased by 20%, the electricity production costs drop by 6.08 to 6.82 US$/MWh resp. 17%. If the full load hours of the electricity generation plant are reduced by 20%, the electricity production costs increase by 9.12 to 10.23 US$/MWh resp. 25 %. The results for the electricity cost are summed up in the following table.

Table 32: Results of sensitivity analysis for different electricity generation for location Pomona – absolute values of LCOE in US$/MWh for different full load hours.

	FLH -20%	FLH Reference value	FLH+20%
Electricity generation		**LCOE in US$/MWh**	
WF/CP	45,61	36,49	30,41
WF/Po	48,79	39,03	32,53
HP/CP	48,14	38,51	32,09
HP/Po	51,16	40,93	34,11

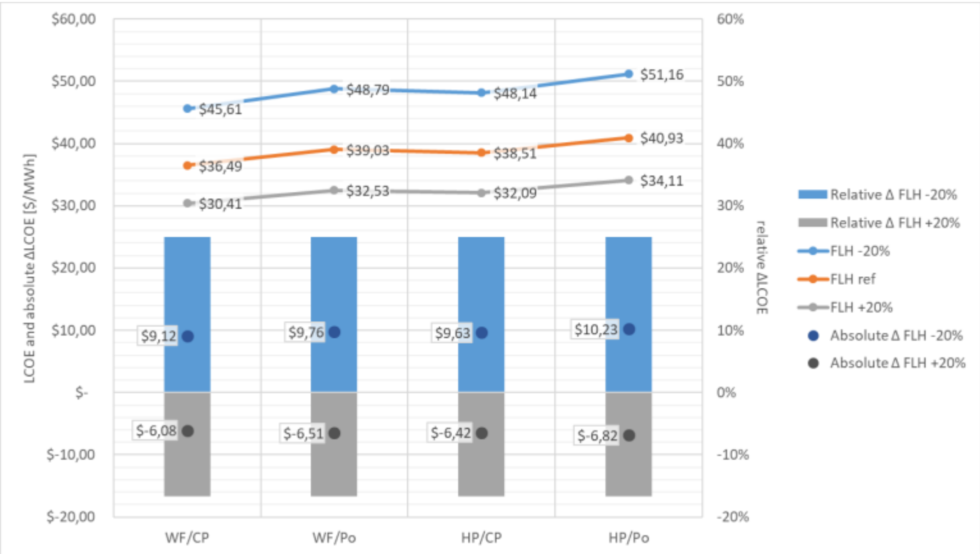

Figure 56: Results of sensitivity analysis for electrolyser location Pomona – absolute values and relative changes of LCOE for different full load hours.

To determine the hydrogen production costs for the scenarios with the higher full load hours, the full load hours of the electrolysers are increased by 20% according to the increase of full load hours of the electricity generation and additionally the changed LCOE for the electricity generation is used. At 20% higher full load hours the hydrogen production costs decrease by 0.44 to 0.92 US$/kg resp. 10 to 15%. At 20% lower full load hours the hydrogen production costs increase by 0.69 to 0.130 US$/kg resp. 15 to 23%.

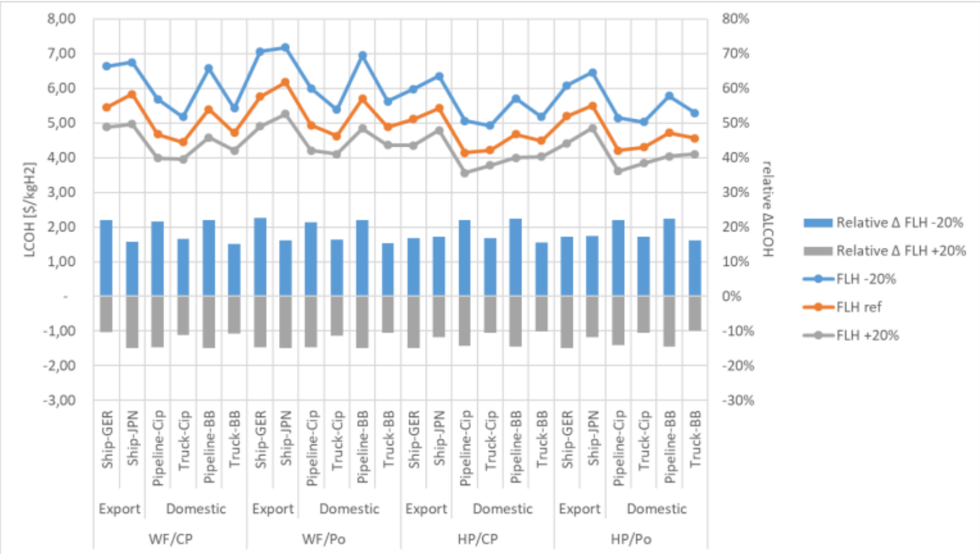

Figure 57: Results of sensitivity analysis for electrolyser location Pomona – absolute values and relative changes of LCOH for different full load hours.

The next slides summarize the results for the changes in the various parameters for four selected scenarios. This shows which parameter has a high influence on the LCOH and which parameter has a small influence on the LCOH. Two domestic scenarios were used, once with truck and once with pipeline transport, and two export scenarios were used for each consumer country Japan and Germany.

The parameters with the highest influence are the full load hours and the CAPEX of all components together (electricity production, grid connection, electrolyser, infrastructure, and transport). Also the interest rate has a high influence. The Cost escalation rate has a high influence when the value is increased significantly.

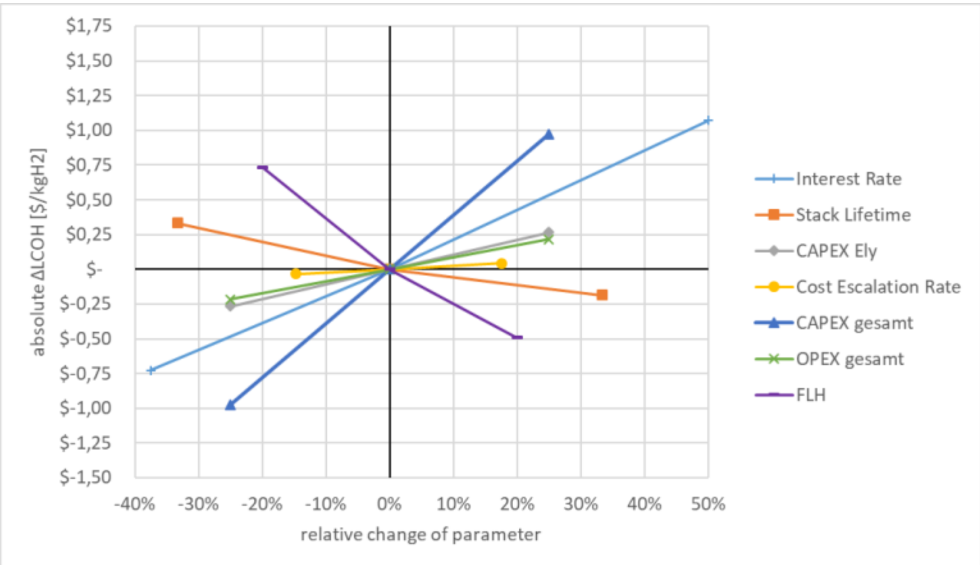

Figure 58: Results of sensitivity analysis for scenario Po-WF/CP-domestic-100-Truck-Cip – variation of LCOH for various parameters.

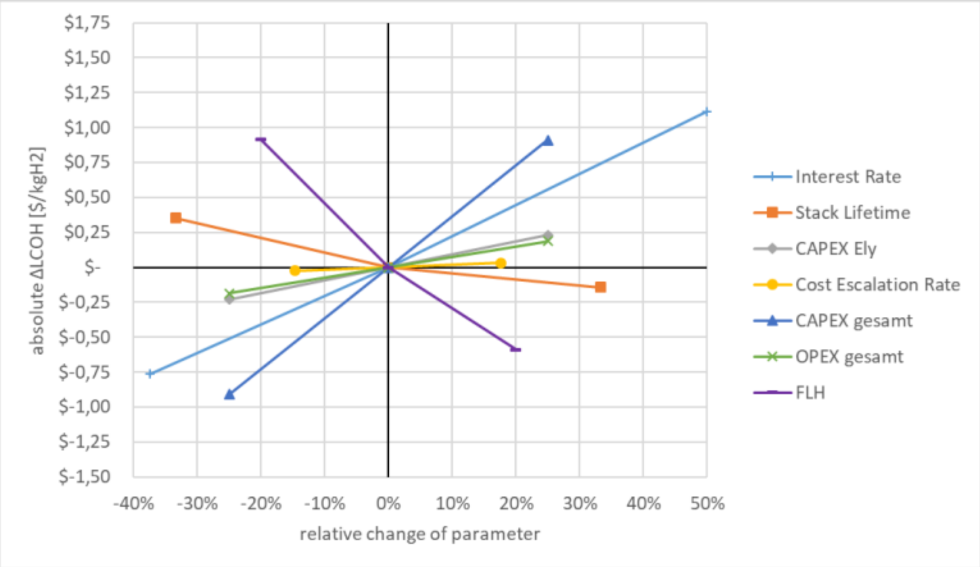

Figure 59: Results of sensitivity analysis for scenario Po-WF/CP-domestic-100-Pipeline-Cip – variation of LCOH for various parameters.

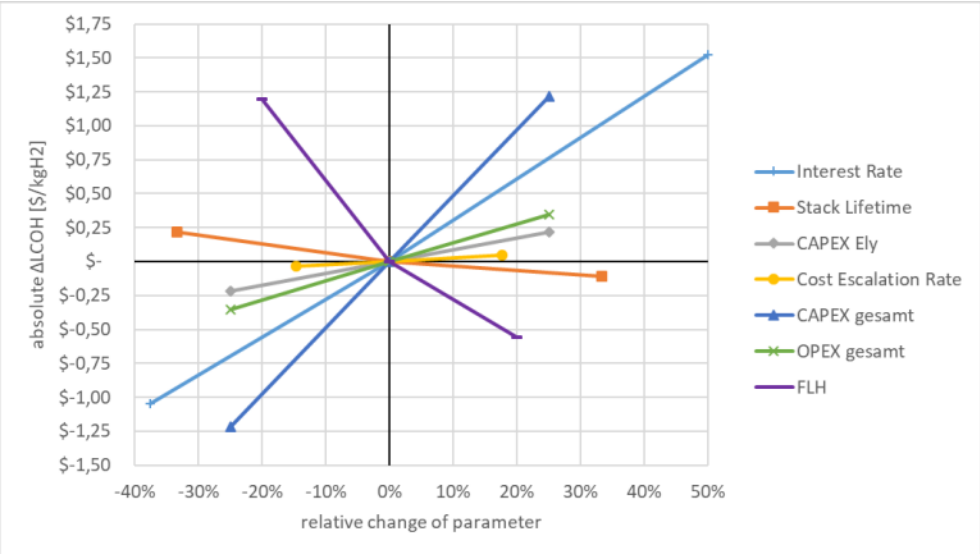

Figure 60: Results of sensitivity analysis for scenario Po-WF/CP-export-500-GER – variation of LCOH for various parameters.

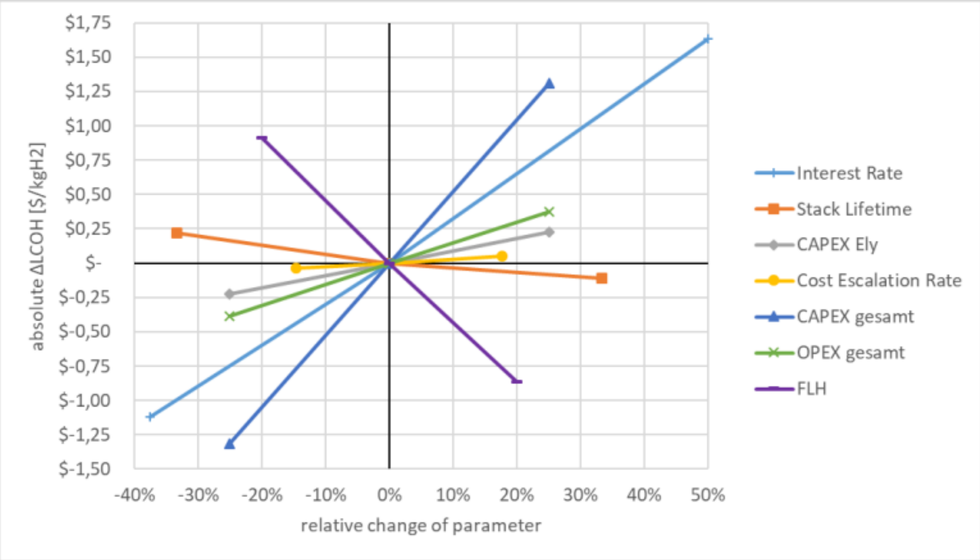

Figure 61: Results of sensitivity analysis for scenario Po-WF/CP-export-500-JP variation of LCOH for various parameters.

6.6 Description of selected scenarios

In the following, two scenarios each for domestic use and export of hydrogen were described in detail. The selected scenarios are

- domestic scenario with lowest hydrogen production costs (location El Chocon)
- domestic scenario with low hydrogen production costs (location Pomona)
- export scenario with lowest investment costs
- export scenario with lowest hydrogen production cost.

6.6.1 Domestic scenario with lowest hydrogen production costs (location El Chócon)

The domestic scenario with lowest hydrogen production costs is Cho-WF/CP-domestic-100-pipeline-PH. The information for this scenario is summarized below:

- Location of electrolyser: El Chócon
- Electrolyser capacity: 100 MW, produced hydrogen: 8,843 tons/year
- Electricity generation: 105 MW wind farm in Cerro Policia (note: no hybrid plants were calculated for El Chocon)
- Grid connection: Use of existing electricity grid (500 kV), construction of 5 km of electricity line up to the 500/132 kV substation.
- Water supply: connection to Rio Limay; Water quality sufficient: only simple water treatment necessary
- Hydrogen consumer: refinery in Plaza Huincul
- Transport by pipeline
- Total investment costs: 282 Mio US$ (see Table 33)
- OPEX: 5.3 Mio US$ (for first year, without cost increase)
- Resulting LCOH / hydrogen production costs: 3.83 US$/kg
  → also if the hydrogen will be transported to Cipolletti and also if trucks are used instead of pipelines the LCOH are below 4 US$/kg (for the above mentioned

conditions) and also the investment cost are only a little bit higher → detailed site assessment and project development necessary.
- Year of installation: 2025

Table 33: Investment costs for scenario Cho-WF/CP-domestic-100-pipeline-PH

Investment costs	Mio US$
Electricity generation	136.8
Electricity Grid	25.7
Electrolyser (100MW)	83.4
Water supply	11.0
Transport of hydrogen	24.9
Sum	**281.9**

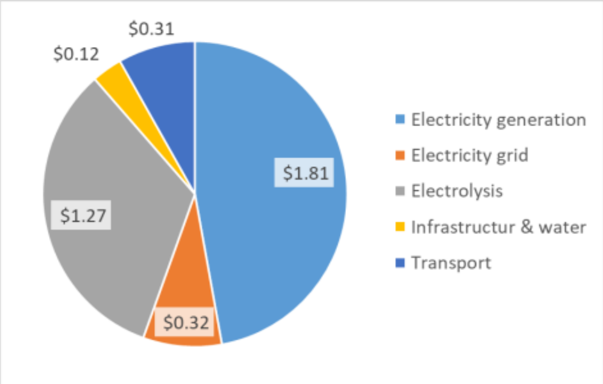

Figure 62: Composition of hydrogen production costs for scenario Cho-WF/CP-domestic-100-pipeline-PH

Breakdown of LCOH into CAPEX and OPEX (example):

- LCOH / hydrogen production costs: 3.83 US$/kg
- Electricity costs share of LCOH: 47%
- Electrolyser costs share of LCOH: 33%
- Electricity costs not in OPEX included but in CAPEX
- CAPEX share of LCOH: 82% (3.14 US$/kg)
- OPEX share of LCOH : 18% (0.70 US$/kg).

6.6.2 Domestic scenario with low hydrogen production cost (location Pomona)

Another domestic scenario with very low hydrogen production costs is Po-HP/CP-domestic-100-pipeline-Cip. The information for this scenario is summarized below:

- Location of Electrolyser: Pomona
- Electrolyser capacity: 100 MW, produced hydrogen: 12,090 tons/year
- Electricity generation: Hybrid plant in Cerro Policia: 130 MW wind farm + 60 MW PV → higher full load hours for electrolyser than by wind plant, therefore more produced hydrogen
- Grid connection: Use of existing electricity grid (500 kV), construction of 9.8 km of electricity line up to the 500/132 kV substation.
- Water supply: Using the existing canal between Pomona and SAO, construction of 11 km of additional canal; water quality sufficient: only simple water treatment necessary

- Hydrogen consumer: Cipoletti
- Transport by pipeline → transport by truck nearly the same costs (for the above mentioned conditions) → detailed site assessment necessary
- Total investment costs: 426 Mio US$ (see Table 34) → higher investment costs due to the installed hybrid plant with higher capacities
- OPEX: 8.1 Mio US$ (for first year, without cost increase)
- Resulting LCOH / hydrogen production costs: 4.15 US$/kg → low hydrogen production costs due to higher amount of produced hydrogen
- Year of installation: 2025

Table 34: Investment costs for scenario Po-HP/CP-domestic-100-pipeline-Cip

Investment costs	**Mio US$**
Electricity generation	213.4
Electricity Grid	26.9
Electrolyser (100MW)	83.4
Water supply	11.7
Transport of hydrogen	90.4
Sum	**425.9**

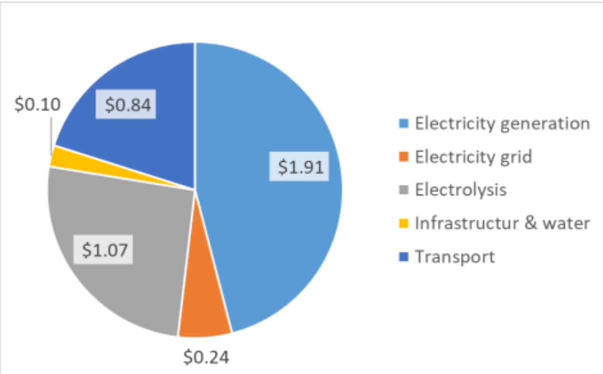

Figure 63: Composition of hydrogen production costs for scenario Po-HP/CP-domestic-100-pipeline-Cip

6.6.3 Export scenario with lowest investment costs

The export scenario with lowest investment costs is LR-WF/LR-export-500-ship-GER. The information for this scenario is summarized below:

- Location of electrolyser: Laguna de la Retencion
- Electrolyser capacity: 500 MW, produced hydrogen: 41,186 tons/year
- Electricity generation: 526 MW wind farm in Laguna de la Retencion
- Grid connection: Direct connection between wind farm and electrolysis, installation of a substation
- Water supply: Using the existing canal between Pomona and San Antonio Oeste; water quality sufficient: only simple water treatment necessary
- Port: San Antonio Este. → Suitable for exporting initial amounts of hydrogen. Needs to be expanded when capacity is ramped up.
- Hydrogen export: consumer Europe (Germany)
- Transport includes pipeline to port, storage, liquefaction, ships
- Resulting LCOH / hydrogen production costs: 5.49 US$/kg
- Total investment costs: 1,807 Mio US$ (details see Table 35)
- OPEX: 49.9 Mio US$ (for first year, without cost increase)
- Year of installation: 2030

Table 35: Investment costs for scenario LR-WF/LR-export-500-ship-GER

Investment costs	Mio US$
Electricity generation	684.2
Electricity Grid	123.3
Electrolyser (100MW)	361.8
Water supply	55.2
Transport of hydrogen	583.0
Sum	**1,807.4**

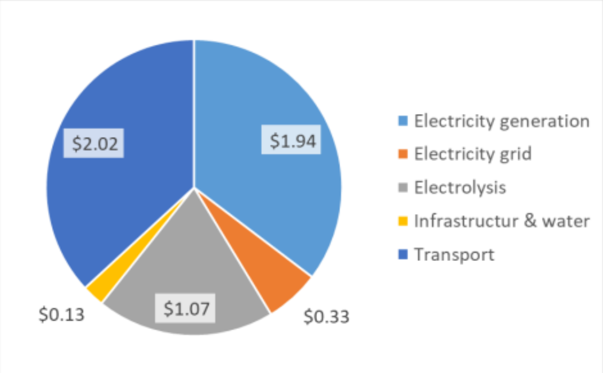

Figure 64: Composition of hydrogen production costs for scenario LR-WF/LR-export-500-ship-GER

6.6.4 Export scenario with lowest hydrogen production cost

The export scenario with lowest hydrogen production costs is LR-HP/CP-export-500-ship-GER. The information for this scenario is summarized below:

- Location of electrolyser: Laguna de la Retencion
- Electrolyser capacity: 500 MW, produced hydrogen: 61,174 tons/year
- Electricity generation: Hybrid plant in Cerro Policia: 675 MW wind farm + 350 MW PV → higher full load hours for electrolyser than by wind plant, therefore more produced hydrogen
- Grid connection: It is assumed that a 500 kV line will be built until 2030. Within the project, a grid connection with a substation is planned.
- Water supply: Using the existing canal between Laguna de la Retencion and San Antonio Oeste; water quality sufficient: only simple water treatment necessary
- Port: San Antonio Este.
- Hydrogen export: Consumer: Europe (Germany)
- Transport includes pipeline to port, storage, liquefaction, ships
- Resulting LCOH / H2 production costs: 4.92 US$/kg → lower hydrogen production costs due to higher amount of produced H2

Total investment costs: 2,422 Mio US$ (see
- Table 36) → higher investment costs due to the installed hybrid plant with higher capacities
- OPEX: 67.5 Mio US$ (for first year, without cost increase)
- Year of installation: 2030

Table 36: Investment costs for scenario LR-HP/CP-export-500-ship-GER

Investment costs	Mio US$
Electricity generation	1,136.5

Electricity Grid	123.3
Electrolyser (100MW)	361.8
Water supply	55.2
Transport of hydrogen	745.4
Sum	**2,422.2**

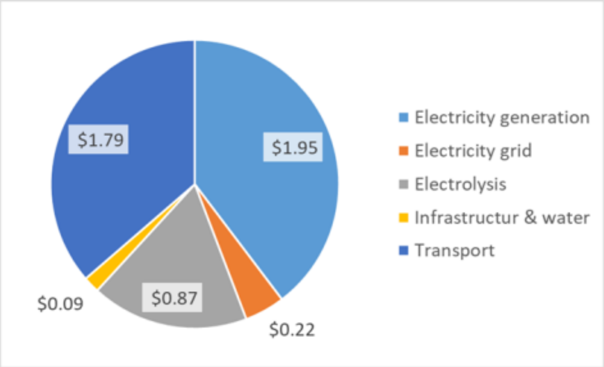

Figure 65: Composition of hydrogen production costs for scenario LR-HP/CP-export-500-ship-GER

7
Hydrogen policy recommendations

This chapter aims to identify possible steps on Rio Negro's and Argentina's path to the global hydrogen economy and to provide guidance on how hydrogen production can be established.

In the last two years, various countries around the world have published hydrogen-related initiatives and are thus pushing the development of a global green hydrogen economy.

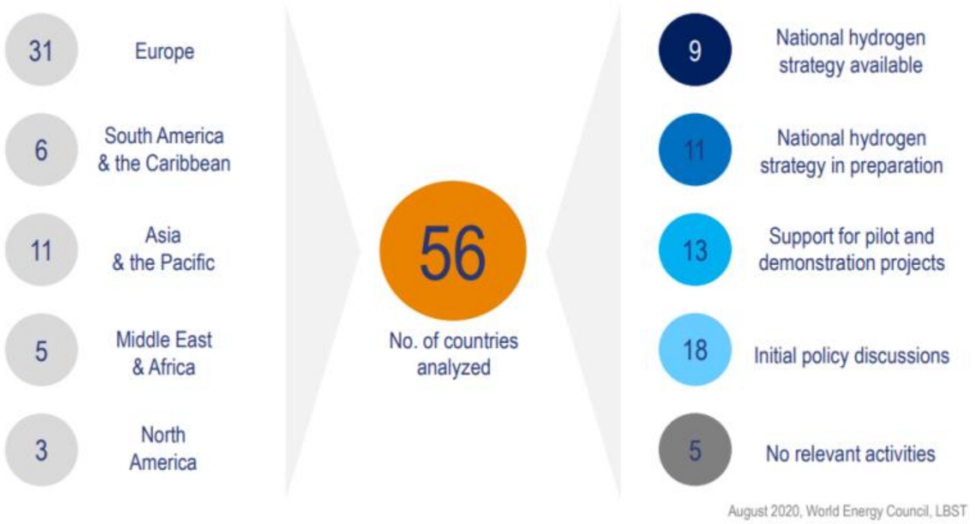

Figure 66: Overview H2-strategies and activities (Rolle et al. 2020)

Not only are national hydrogen strategies being published, but international funding instruments are also being set up to prepare for large-scale green hydrogen imports. During „Berlin Energy Transition Dialogue" in March 2021, the German Government announced that it will start implementing the 'H2 Global' funding concept. At the focus of the 'H2 Global' concept is a foundation that supports consortia to enter into the production of green hydrogen abroad. The consortia must prevail in an auction process for the long-term supply of green hydrogen to Germany. On the buyer side, the companies that are willing to pay the highest price for the hydrogen receive an annual award.

Argentina is one of 21 worldwide active members, working on ISO/TC 197[1]. In 2007 Argentina published its own national hydrogen safety standard IRAM-ISO 15916. Furthermore a Hydrogen Promotion National Law was published in 2006 in order to declare the interest of technology, production, use and applications of hydrogen. In the context of this law, a Hydrogen National Plan was prepared in 2013. The law and the national plan would need an update before regulation and implementation.

[1] Scope of ISO/TC 197: Standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen.

7.1 Policy and regulatory aspects of hydrogen production

In the past - due to oil price shocks, aspects of peak oil demand or air pollution there have been repeated efforts to ascribe greater importance to hydrogen. Drivers of the current new wave of green hydrogen, meaning conditions that support green hydrogen, include the following:

1. Low variable renewable energy (VRE) electricity costs.
2. Technologies ready to scale up
3. Benefits for the power system
4. Government objectives for net-zero energy systems
5. Broader use of hydrogen
6. Interest of multiple stakeholders

Those drivers face barriers to the uptake of green hydrogen that make it difficult to utilise the gas economically. Those barriers include the following aspects:

1. High production costs
2. Lack of dedicated infrastructure
3. Energy losses
4. Lack of value recognition
5. Need to ensure sustainability

A hydrogen strategy can support the ramp-up of green hydrogen production. Typically, there are three levels of hydrogen policy support:

1. First stage: Technology readiness
2. Second stage: Market penetration
3. Third stage: Market growth

Example of the German initiative on power fuels

The regions in the world with a high population density and high per capita energy consumption as in the case of central Europe and Japan are relying on imported fossil fuels today and will be depending on importing green fuels in the future in order to meet agreed greenhouse gas reduction targets. In the light of such a future, the German Energy Agency DENA has initiated the "Global Alliance Powerfuels" in 2018 "with the strategic objective of fostering the development of a global market for powerfuels". The main goals are to raise awareness and acceptance, to stimulate global project development and to enhance the regulatory framework to stimulate demand" (Crone et al. 2019)

The initiative has identified carbon pricing, adaptation of fuel prices i.e. through phasing out fossil fuel subsidies and further instruments for the development of the infrastructure required for the large scale production of alternative fuels, as the enabling policies to contribute to the further development of renewable energies in general.

Some of the key instruments identified are feed-in tariffs for renewable electricity, global emission and efficiency standards, subsidy programs for R&D, CAPEX as well OPEX support as market incentives for new technologies, actions and tenders in the power sector and for power fuels and finally fuel blending quotas as they already exist in Europe and in the US.

The economics and success of a large scale green hydrogen or PtL production for export from i.e. Argentina will be depending on the creation of the international markets based on the actions and policies summarized above. In addition, there will be other regions, which have the opportunity to produce green hydrogen at similar low cost due to comparable resource conditions. Examples are the results from studies covering Chile, Australia and South Africa. This will in the future potentially create a very competitive international market i.e. for green powerfuels and success will be depending on consistent and efficient policies, strong governments and industrial commitment.

In order to achieve competitiveness, the establishment of a domestic hydrogen market, the implementation of the required market and technical regulations as well as creating public awareness and acceptance have to be considered key enabling policies. In the case of Argentina, significant domestic hydrogen markets exist. However, the economics of green hydrogen require market incentives in order to create a business case for the industries involved. Establishing such policy instruments would accelerate the capacity building and commercial experience in green hydrogen production, the development of a local supply chain and thereby increase the potential share of the value chain in the country. This will at the same time reduce the dependency on foreign technology and investment for the roll-out of the hydrogen market and ramp-up of production capacity.

Another important aspect of capacity building is international collaboration in research and development and the public support for the implementation of pilot and demonstration projects in an early phase.

7.2 Hydrogen Policy making

As mentioned above, there are many recently announced hydrogen strategies that typically result from a long process and mark the beginning of a new wave of policies. Figure 67 shows common steps towards publishing a National strategy.

Figure 67: Steps leading to the formulation of a national strategy (International Renewable Energy Agency (IRENA) 2020)

The strategy process starts with the establishment of R&D programmes to understand the fundamental principles of the technology including the development of the knowledge base that will inform future stages, and to explore multiple technologies and possibilities. At the same time such programmes foster the capacity building in the region and country by gaining technical know-how, creating practical experience from research and demonstration projects and establishing education and training.

In the next step, a vision document clarifies the “why”: “why hydrogen”, “why this jurisdiction”, and “why now”. It has the aim to guide research, industry efforts and early demonstration programmes. These documents usually emerge by cooperation of governments and private actors attracted by the growth prospects of breakthrough applications.

Next step is a roadmap. It has the aim to define the activities necessary to achieve the objectives in order to better assess the potential for hydrogen. Short-term actions needed are identified to advance deployment. Additionally the research areas with the highest priority and the applications where demonstration projects are most needed are defined.

The strategy itself, finally, defines the targets, addresses concrete policies and evaluates their coherence with existing energy policy. It doesn’t only cover specific direct policies but also includes integrating and enabling policies that are needed to ensure deployment across the system, such as those that support the development of a skilled workforce. The strategy is informed by extensive scenario modelling, often with input from academia and industry.

Throughout the process of devising a strategy, public-private-partnerships (PPP) can be formed in order to create a general consensus about the vision and coordinate potential efforts.

Examples for recent hydrogen strategies are the German National hydrogen strategy published in June 2020 as well as the European Hydrogen Strategy (published in 2020): “Reaching the 2030 goals”:

- 40 GW electrolyser capacity in Europe producing up to 10 MT/yr of renewable hydrogen
- estimated to require investment of EUR 24-42 billion for electrolyser capacity
- in addition to EUR 220-340 billion for 80-120 GW of additional renewable power generation capacity
- Investments of EUR 65 billion for infrastructure and EUR 11 billion for retrofitting existing natural gas plants.” (International Renewable Energy Agency (IRENA) 2020)

7.3 Potential instruments of policies for green hydrogen and their impact

Policies have the aim to address barriers identified in order to support the green hydrogen to advance from niche to mainstream and be part of the energy transition – some of them are relatively consistent across end uses (the cost barrier being the main one), some are sector specific. In this chapter, specific policies and measures are presented for selected segments of the hydrogen value chain.

Figure 68 provides an overview of barriers to sections of the green hydrogen production chain and related policy options to overcome those barriers.

Figure 68: Selected barriers and policies for segments of the hydrogen value chain (International Renewable Energy Agency (IRENA) 2020)

Figure 69 shows a chronologically reasonable order of the instruments with regard to the development of a market ramp-up of hydrogen and power-to-X technologies.

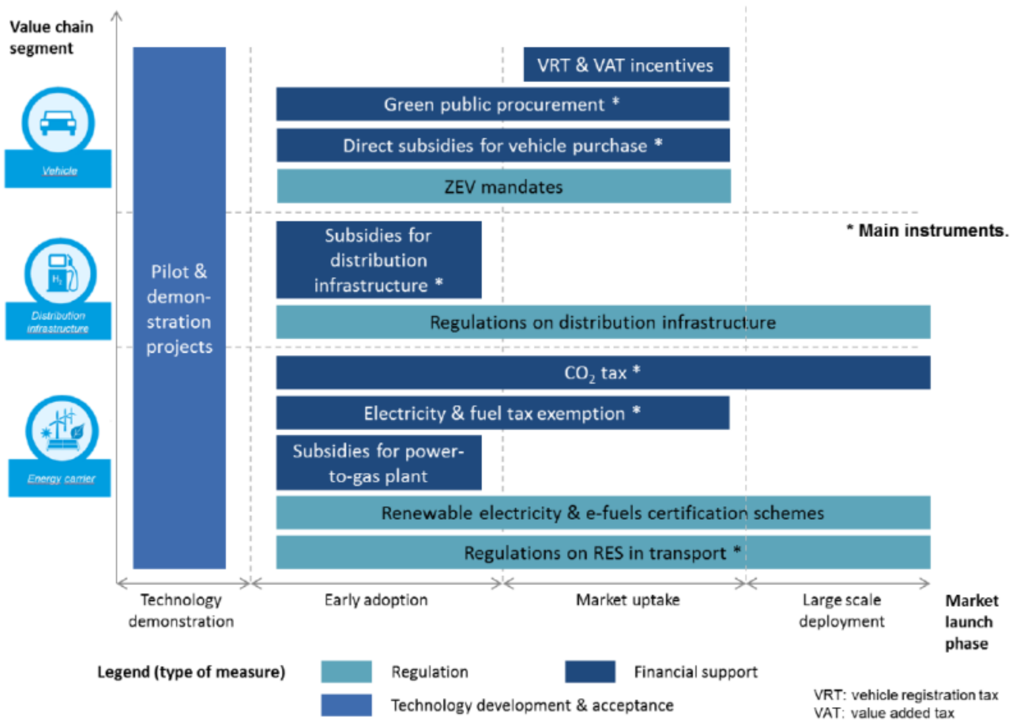

Figure 69: Overview of the relevant policy instruments to be used to support market launch of power-to-gas technologies in the non-individual road transport (Bucy et al. 2016)

For the Rio Negro province, the following steps could support the development of dedicated and comprehensive green hydrogen strategy:

- A programme for capacity building (and regulation development alongside) at provincial and National level
  - Support for public R&D institutions, Bachelor and master courses at universities, PhD programs
  - Education and training in industry (oil & gas, (petro)chemical)
  - Pilot projects at multi MW level
- Stakeholder engagement process
  - In addition to the above: ministries and their agencies
- Strong collaboration required between all stakeholders in particular R&D, universities and industry, regulators

Capacity building is one of the most effective instruments in terms of designing a strategy and implementing a market ramp-up. Collaboration between public R&D institutions, industry and ministries as well as governmental agencies is immensely essential to operate successfully. Additionally first pilot plants lead to a more familiar use of the new technology in order to gain experience for potential large-scale export applications.

Furthermore, decision-makers need to provide a framework in terms of critical institutional and regulatory aspects:

- National PtX roadmap (as described above)
- Necessary standards and regulations
- Phase-out subsidies for fossil fuels

Establishing such policy instruments in Argentina would accelerate the capacity building and commercial experience in green hydrogen production, the development of a local supply chain and thereby increase the potential share of the value chain in the country. This will at the same time reduce the dependency on foreign technology and investment for the roll-out of the hydrogen market and ramp-up of production capacity.

8
Conclusions and next steps

This study on behalf of Government of the Rio Negro province has identified huge opportunities for a cost effective production of green hydrogen based on the exceptional natural resources in the region. The province is well placed to become a frontrunner for the "green hydrogen economy" in Argentina and South America by positioning itself at an early stage of the technology innovation and market implementation of hydrogen production and utilization.

The focus of the study is on analyzing different locations for the production of green electricity from wind and solar as well as identifying suitable hydrogen production sites as well as the corresponding infrastructure for domestic applications as well as export. For the domestic application a project scale of 100 MW electrolyser capacity has been chosen – in line with other international initiatives. This scale is sufficient to show significant economy of scales effects and put the province on the international landscape of green hydrogen projects.

For the implementation of a first electrolyser system with 100 MW in 2025 (domestic scenario), the cost optimum will be achieved if the electrolyser is located in El Chocón and the consumer is in Plaza Huincul or Cipolletti (hydrogen production cost < 4 US$/kg). But also for the other electrolyser locations, scenario-combinations can be found in which costs are below 4.5 US$/kg.

In the longer term, there are huge opportunities for hydrogen exports i.e. in liquid form – other options were not investigated in the scope of this study. However, the production and export of i.e. green chemical feedstock such as ammonia or methanol provide relevant alternatives to the liquefaction and should be investigated in detail in the context of future strategic considerations and roadmap generation.

For the electrolyser plant with 500 MW capacity in 2030 with the aim of export of hydrogen, several locations are possible, where hydrogen costs of about 5 - 5.20 US$/kg (including transport to Germany) can be achieved. This corresponds to a cost of about 4 €/kg and is thus competitive with i.e. costs from offshore hydrogen from the North Sea.

For the implementation of a 100 MW electrolyser in 2025 (domestic scenario), the investment costs are approximately 280 to 300 million US$ (including electricity generation and transport) in the most cost-effective scenarios. For the implementation of a 500 MW electrolyser in 2030 (export scenario), the total investment costs amount to at least 1.8 to 2 billion US$.

Green hydrogen is becoming more and more cost-competitive mainly because of reductions in CAPEX (electrolysers, storage, balance of system) and OPEX (LCOE, specific energy consumption, longer lifetime). Projections indicate that for 2030 electrolysers would cost around 25% -50% less than current prices and LCOE will potentially drop to values as low as 25 €/MWh.

Considering that energy represents approximately 45-70% of the overall green hydrogen production costs and having access to very large amounts of renewable energy in the province allows green hydrogen to reach the relevant volumes and scale to be cost competitive in comparison with blue hydrogen by 2030.

Due to its unique natural conditions and location, the Argentinean Patagonia is probably the region of the world where the largest green hydrogen production scale can be achieved. Below the 40th latitude south, it is the only solid ground on earth, where meteorological systems reach the continent, generating the most powerful, reliable and constant wind energy resources in the world, while larger amounts of water are available flowing from “Los Andes” mountain range to the Atlantic Ocean every day with very little human intervention.

Currently, Argentina possess a local grey hydrogen market (hydrogen produced by steam reforming of methane), where 327,695 ton/a are being consumed mainly in the petrochemical (85%), chemical (8%) and refining (7%) industries. Therefore, transition from grey hydrogen towards a green hydrogen economy should beside the transport sector also consider these industries.

Industry in Argentina should be considered as a fast trigger for domestic green hydrogen because replacing only a small percentage of the actual hydrogen demand, would require hundreds of MW of electrolysers. Although, competitiveness with grey hydrogen might be achieve in a mid-term (after 2030), first frontrunners decision may be triggered by carbon tax policy and achieve this scenario before. At the same time, lock-in effects and the potential risk for stranded assets from investment into fossil energy based production and transport infrastructure should be considered with caution.

To resume, in order to achieve competitiveness, the establishment of a domestic hydrogen market, the implementation of the required market and technical regulations as well as creating public awareness and acceptance have to be considered key enabling policies. All of these aspects can be implemented and improved alongside the proposed hydrogen production projects at industrial scale.

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10 Annex

10.1 Figures of distances

In the following, several figures are presented which show the distances between the different elektrolyser locations and the consumer locations respectively the port in San Antonio Oeste.

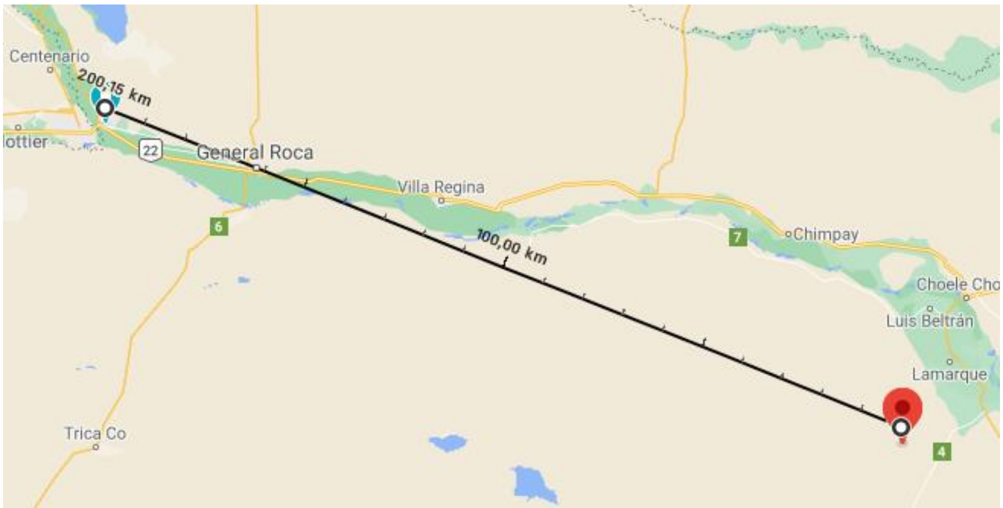

Figure 70: Distance between Pomona and Cipoletti for pipeline transport (=direct connection of the locations)

Figure 71 Distance between Pomona and Cipoletti for truck transport (=transport by road)

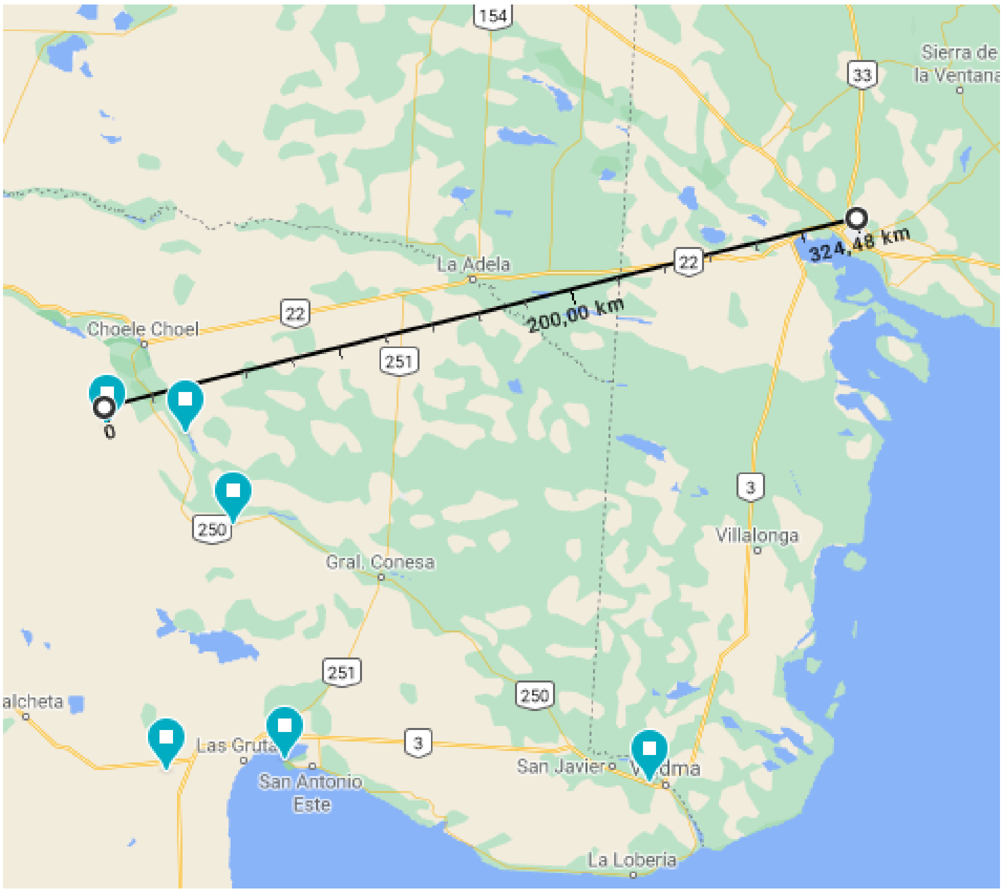

Figure 72 Distance between Pomona and Bahia Blanca for pipeline transport (=direct connection of the locations)

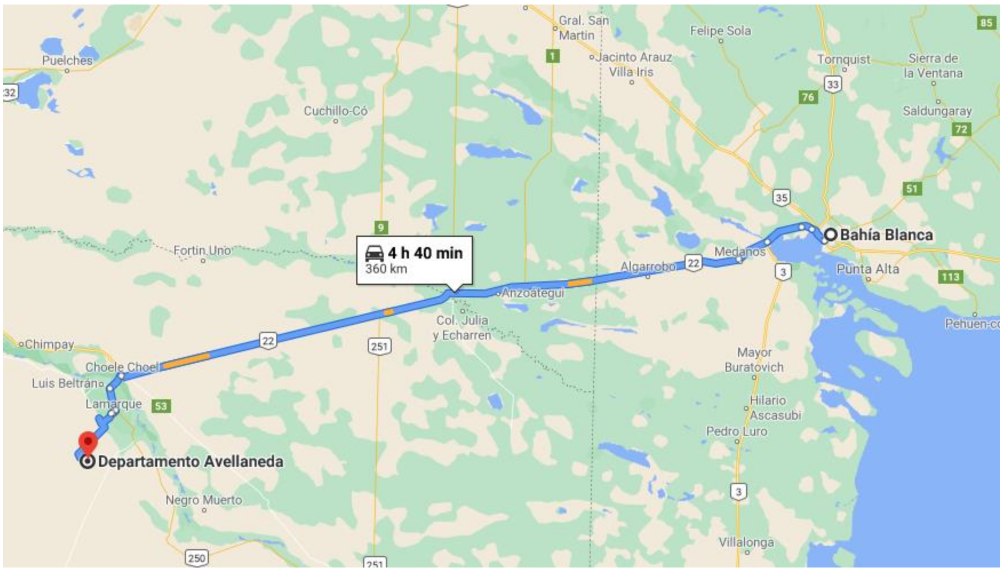

Figure 73 Distance between Pomona and Bahia Blanca for truck transport (=transport by road)

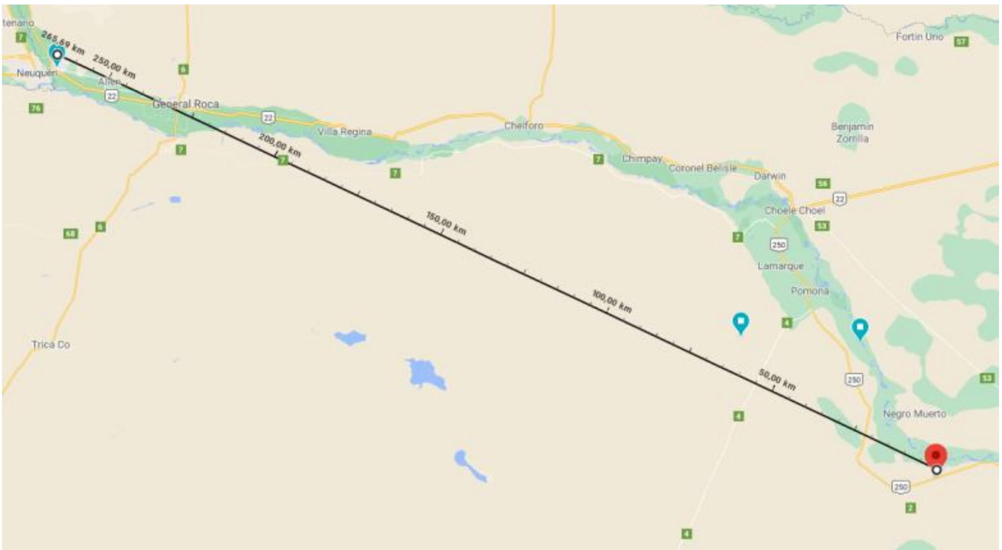

Figure 74 Distance between El Solito and Cipoletti for pipeline transport (=direct connection of the locations)

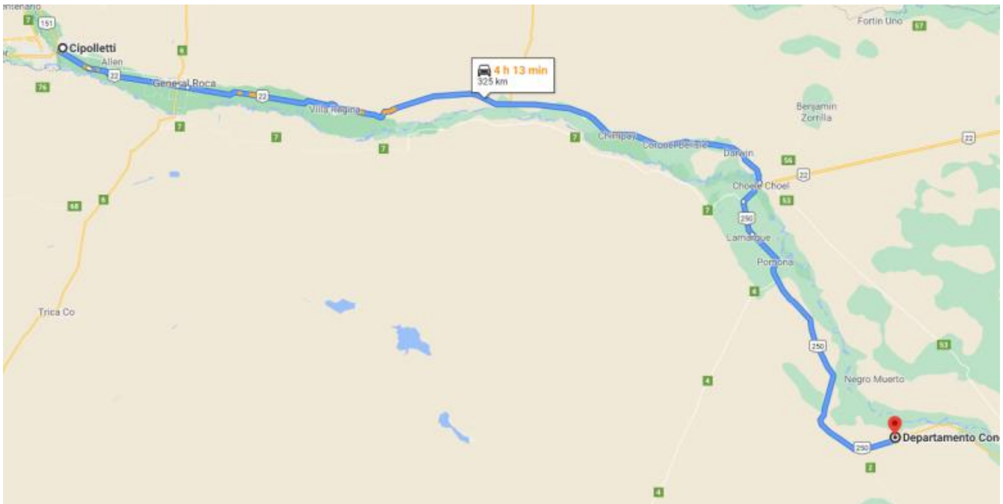

Figure 75 Distance between El Solito and Cipoletti for truck transport (=transport by road)

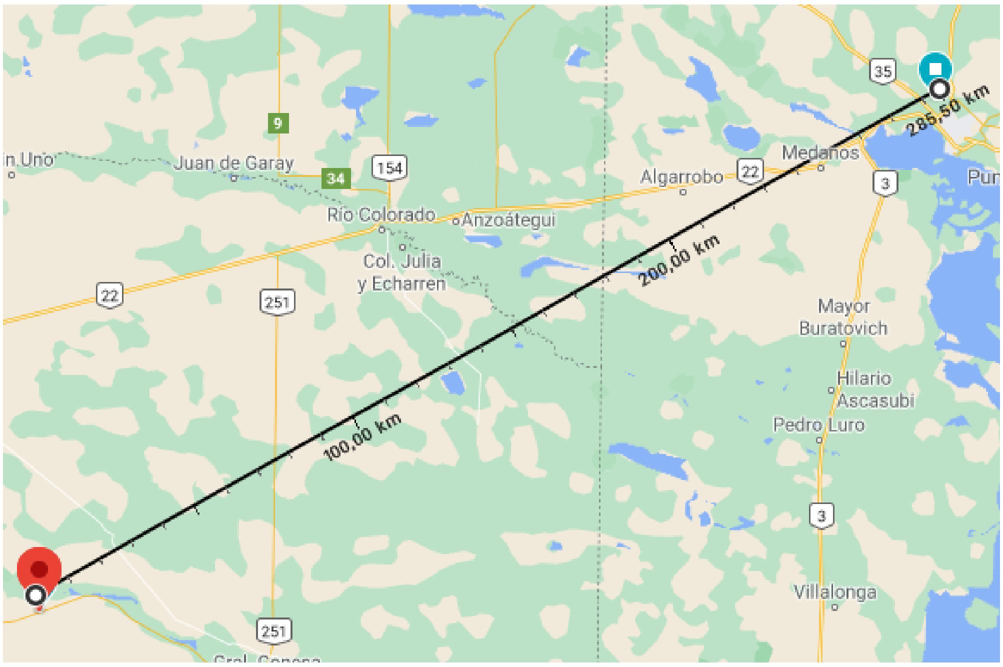

Figure 76 Distance between El Solito and Bahia Blanca for pipeline transport (=direct connection of the locations)

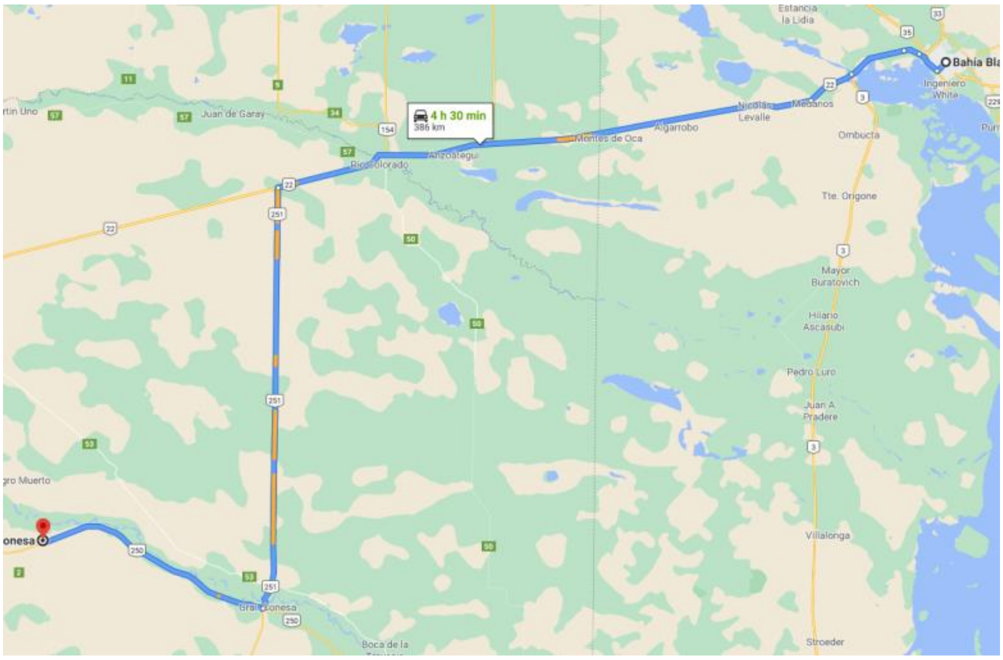

Figure 77 Distance between El Solito and Bahia Blanca for truck transport (=transport by road)

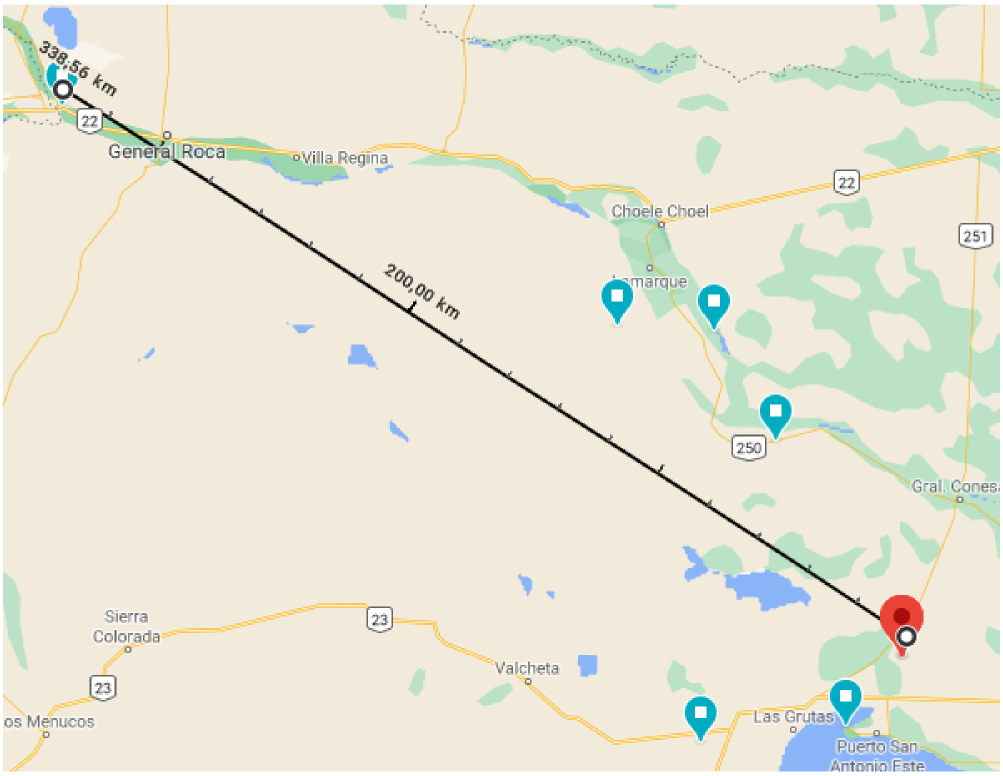

Figure 78 Distance between Laguna de Retención and Cipoletti for pipeline transport (=direct connection of the locations)

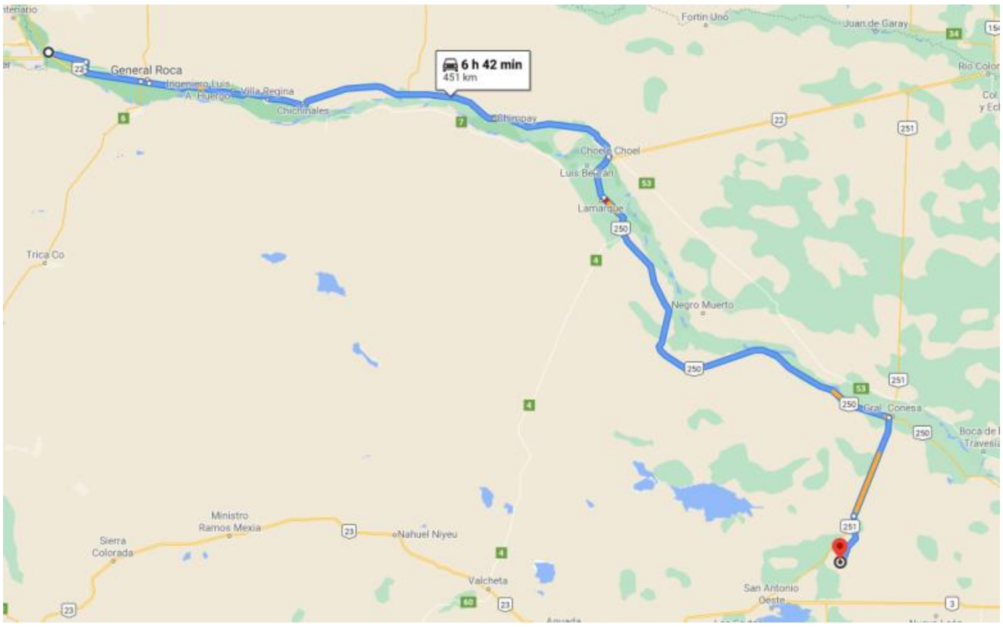

Figure 79 Distance between Laguna de la Retención SAO and Cipoletti for truck transport (=transport by road)

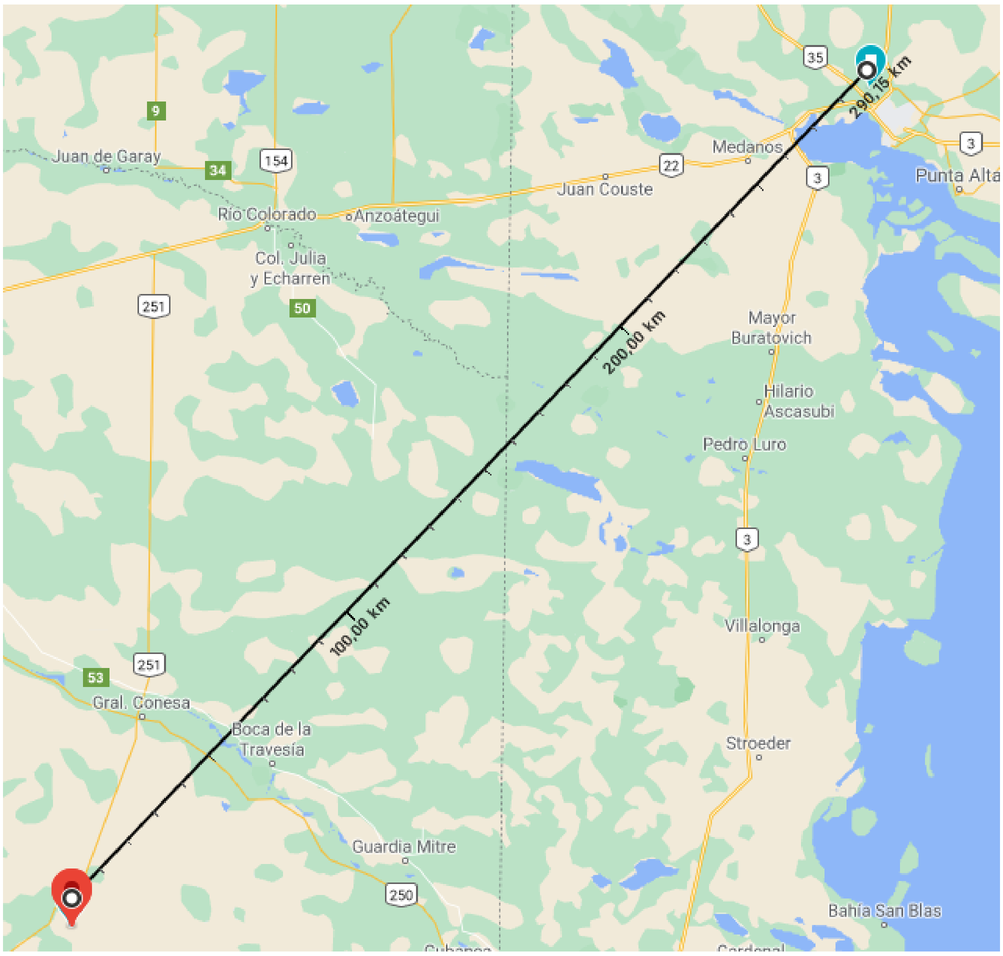

Figure 80 Distance between Laguna de la Retención and Bahia Blanca for pipeline transport (=direct connection of the locations)

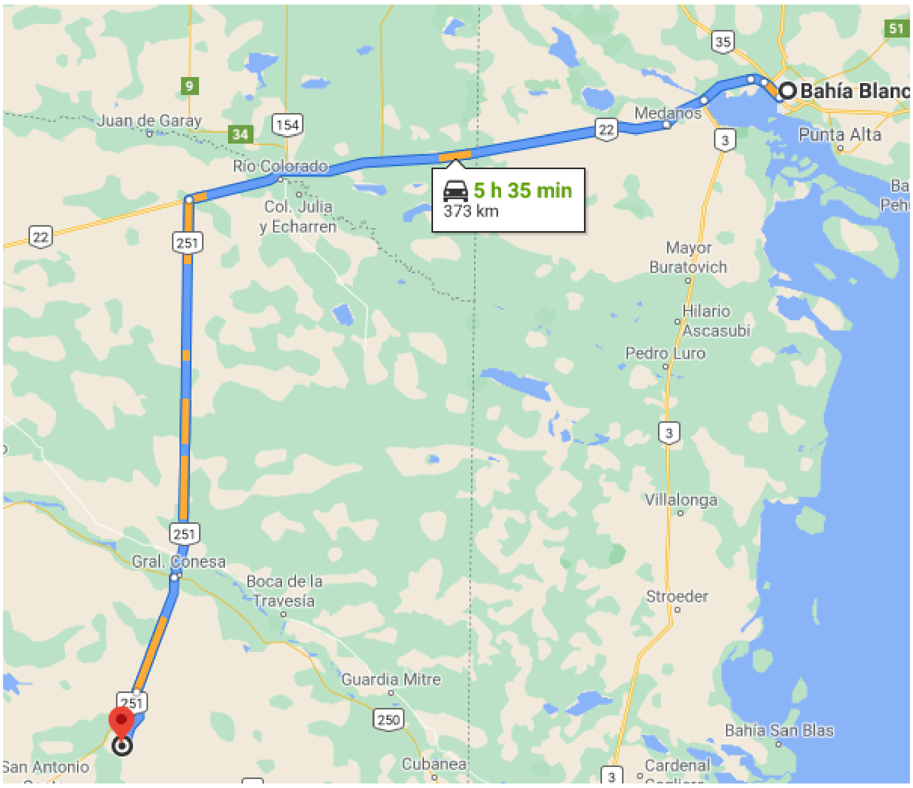

Figure 81 Distance between Laguna de la Retención and Bahia Blanca for truck transport (=transport by road)