THESIS WORK

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Use of energy surplus from local renewable sources, to produce electrolytic hydrogen for electricity generation at isolated places in Argentina

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Declaration of Authorship

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Place, Date

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Abstract

The aim of this project is to study the use of energy surplus from local renewable sources at isolated places in Argentina, to produce electrolytical hydrogen as clean fuel for electricity generation. Furthermore, the hydrogen production is seen as a storage technology to attenuate intermittent power supplies to microgrids. Significant knowledge, concerning Hydrogen production, storage and combustión, is available in Argentina at lab-prototype stage. Although experimental research is still required, this work is an approach to the utilization of the existing technology.

Mostly, micro-grids depend on expensive energy generation, as gas turbines or diesel engines that have to work out of their optimal operating point.

As case study, it is considered the city of Río Grande, placed at the province of Tierra del Fuego in Argentina, because it is not connected to the national grid and shows excellent wind conditions.

Together with Río Grande, there are other micro-grids in the region, which could benefit from the incorporation of energy storage technologies and rely on renewable energy.

The analysis of Río Grande's energy situation, as well as the potential use of wind energy and Hydrogen storage, have shown synergies to reduce energy costs and emissions. Although a general solution was not reached, a scenario is shown in which the hydrogen production and the storage capacity are optimal to offer insight into the problematic and serve as reference for further investigations.

Resumen

El objetivo de este proyecto es estudiar el uso del excedente de energía de fuentes renovables locales en lugares aislados de Argentina para producir hidrógeno electrolítico como combustible limpio para la generación de electricidad. La producción de hidrógeno se considera además una tecnología de almacenamiento para atenuar las fuentes de alimentación intermitentes.

En Argentina, en la etapa laboratorio-prototipo, se encuentran disponibles importantes conocimientos sobre producción, almacenamiento y combustión de hidrógeno. Aunque todavía se requiere una gran cantidad de investigación experimental, este trabajo es un enfoque para la utilización de la tecnología existente.

En su mayoría, las microrredes dependen de la generación de energía costosa, como turbinas de gas o motores diesel que deben funcionar fuera de su punto de operación óptimo.

Como caso de estudio, se considera la ciudad de Río Grande, ubicada en la provincia de Tierra del Fuego. en Argentina, porque no está conectado a la red nacional y muestra excelentes condiciones de viento.

Junto con Río Grande, existen otras microrredes en la región, que podrían beneficiarse de la incorporación de tecnologías de almacenamiento de energía y depender de energía renovable.

El análisis de la situación energética de Río Grande, así como el uso potencial de la energía eólica y el almacenamiento de hidrógeno, han mostrado sinergias para reducir los costos de energía y las emisiones. Aunque no se llegó a una solución general, se muestra un escenario en el que la producción de hidrógeno y la capacidad de almacenamiento son óptimas para ofrece información sobre la problemática y servir de referencia para futuras investigaciones.

Zusammenfassung

Ziel dieses Projekts ist es, die Nutzung von Energieüberschuss aus lokalen erneuerbaren Energiequellen in abgelegenen Orten inhalb Argentiniens zu untersuchen, um somit elektrolytischen Wasserstoff als sauberen Brennstoff für die Stromerzeugung herzustellen.

Darüber hinaus wird die Wasserstoffproduktion als Speichertechnologie zur Dämpfung intermittierender Stromversorgungen für Mikronetze angesehen. Bedeutendes Wissen über Wasserstoffproduktion, -speicherung und -verbrennung ist in Argentinien im Labor-Prototyp-Stadium verfügbar. Obwohl noch viel experimentelle Forschung benötigt wird, ist diese Arbeit ein Ansatz zur Nutzung der vorhandenen Technologie.

Meistens sind Mikronetze auf ungünstige Energieerzeugung angewiesen, wie z.B. Gasturbinen oder Dieselmotoren, die außerhalb ihres optimalen Betriebspunktes arbeiten müssen.

Als Fallbeispiel wird die Stadt Río Grande in der Provinz von Tierra del Fuego in Argentinien betrachtet, weil es nicht an das nationale Stromnetz angeschlossen ist und hervorragende Windbedingungen aufweist.

Zusammen mit Río Grande gibt es in der Region weitere Mikronetze, die von der Einbindung von Energiespeichertechnologien profitieren und auf erneuerbare Energien zurückgreifen könnten.

Die Analyse der Energiesituation von Río Grande sowie die mögliche Nutzung von Windenergie und Wasserstoffspeicher haben Synergien gezeigt, um Energiekosten und Emissionen zu reduzieren. Obwohl keine allgemeine Lösung gefunden wurde, wird ein Szenario aufgezeigt, in dem die Wasserstoffproduktion und die Speicherkapazität optimal sind, um einen Einblick in die Problematik zu bieten und als Referenz für weitere Untersuchungen zu dienen.

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1. Introduction

1.1 Global Review

While the global energy demand increases, extreme scenarios of climate change can be mitigated only by drastically reducing the emission of anthropogenic greenhouse gases.

The International Energy Agency (IEA) [1], [2], estimates that the energy sector produces 83% of the global greenhouse emissions. The Intergovernmental Panel for Climate Change (IPCC) [3], assumes that 44% of the required decarbonization of the economy will come from energy efficiency enhancement, 22% from carbon capture and storage applications, 21% from the use of renewable energy sources, 9% from a slight increase of the Nuclear sector and 4% from the use of biofuels.

The penetration of renewable energy sources in the primary energy matrix will mainly come from wind and solar PV sources, whose instability hinders the control of the grid voltage. Today such problem is solved by expanding the power grid and restricting the operation of the connected renewable power plants. However, since the expansion of the grid has a limit, an increased power demand would difficult the control of voltage intermittences, while further restriction of connected intermittent plants would risk their profit.

On the other hand, worldwide and especially at isolated areas with poor infrastructural development, affordable and reliable energy is a priority. Often the connection to energy distribution networks (electricity, gas) is too costly or technically not feasible, while the efficient transport of conventional fuels is only possible over small and medium distances. In many cases, however, isolated places have natural energy sources (e.g. wind, sun). As an example, Patagonia shows the prototypical situation of a vast region, with very low population density, in which most of the settlements (farms, small or medium communities) do not have network connection and largely use local diesel-powered generators. This region, however, has a high wind power potential, more than enough to meet local energy demands.

To ensure reliable wind or sun energy, a large energy storage capacity is necessary, either for the periods in which the available wind or sun is below or above the required values or during peak load periods, if the design capacity of the plant is exceeded or undershot.

The energy storage capacity must be designed and sized not only to meet a demand-supply balance, but also to ensure systems technically efficient and economically affordable along the time. This would maximize the capacity factor of intermittent renewable power plants and would extend the use of clean energy in the mobility and industrial sectors.

1.2 Renewable Energy and its key role in climate change

The world environment is going through climate changes that have obliged us to an energy transition. Technology innovations and policies are a must in this transition. Renewable energies are produced from non-exhaustible energy sources. As known, have zero emissions and their further incorporation in our energy mix is vital to achieve the Kyoto Protocol [4].

Advantages gained from the incorporation of renewable energies range from economic growth and job creation to emission reduction and climate preservation. Typical renewable energies are: solar, wind, biomass, hydropower, geothermal and tidal. Most of them, are directly or indirectly derived from the sun. [5]

However, incorporation of renewable energies are not straightforward as other problems arise in their application. Typical problems related to renewable energies are power intermittency, geographical dispersion, high capital cost and technology barriers. Numerous studies and investigations were carried on solving this issue.

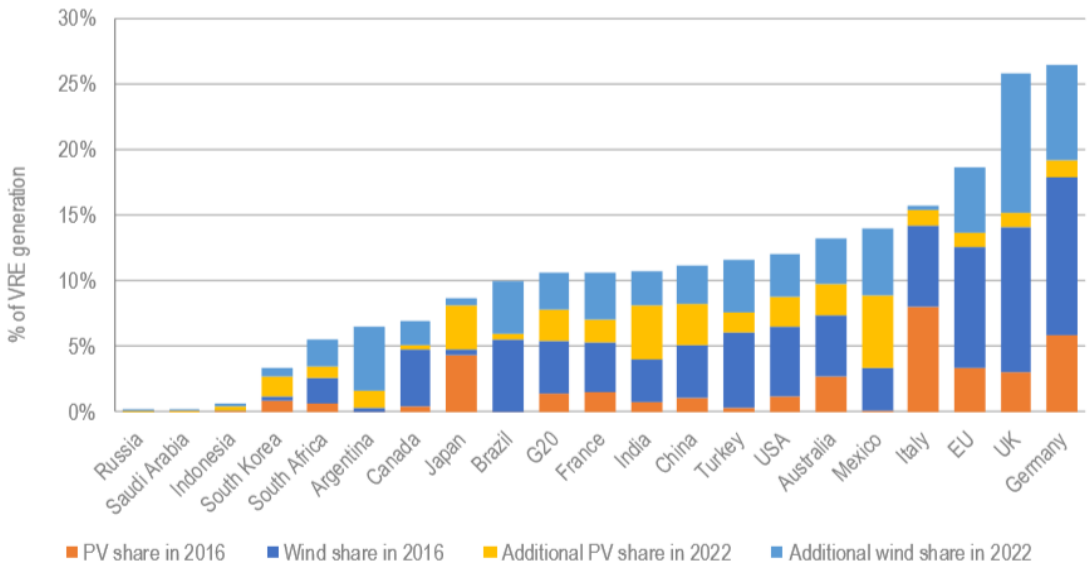


Fig. 1 Share of Renewables in 2016 and 2022 for G20 countries,

IEA, Renewables 2017

Renewable energy technologies are ready for use and costs are declining even faster than conventional fuels. Their generation price is not volatile, nor correlated to global economic issues, as fossil fuels. Wind and solar PV contribution to power systems around the globe is rapidly growing and becoming more important on the energy mix. Fig. 1 shows the share of renewable energies in 2016 and 2022 for G20 countries [6].

Wind energy has become the most economically feasible and fastest growing renewable energy. In 2016, wind energy capacity installed was more than 50GW. The annual increase in the last 5 years was of 15,5% [7].

Fig. 2 shows the energy cost for solar PV and wind over the last years. Beginning with steadily reducing prices and recently with a lower decreasing rate.

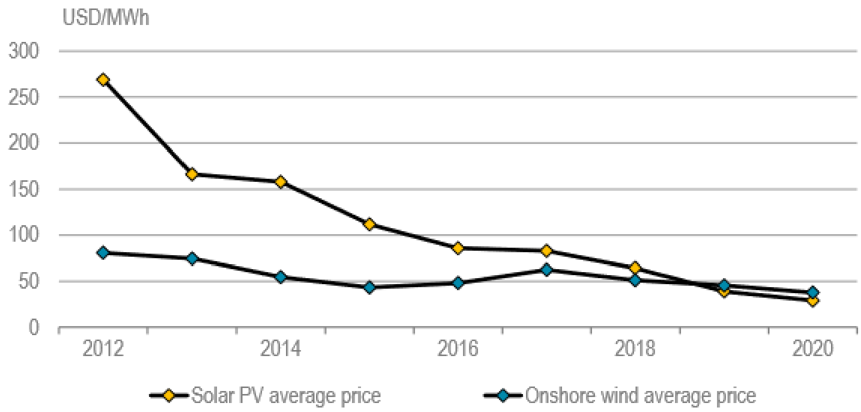


Fig.2 Wind and solar energy prices,

IEA, Renewables 2017.[8]

Renewable Energies have been growing at a rapid rate in recent years, thanks to energy policies and steadily falling prices due to economies of scale [8].

1.3 Energy Matrix in Argentina

Argentina is becoming more interested in a renewable energy regime. Particularly in the policy framework, laws have been passed to accelerate the incorporation of renewable energy. The contribution of renewables to the electricity generation is 1.7% [9]. Although Argentina is the 21st economy of the world (according to their GDP [10]), it is only responsible for 0,8% the total CO2 emitted globally [11]. As it can be seen from the fig.3, almost no coal is used and rather cleaner fuels are applied. Also 30% of its electricity generation comes from hydraulic power over 50 MW.

Both ratios CO2/GDP and CO2/population are adequate for relating overall energy efficiencies for different countries. In 2014 Argentina had 0.3 kgCO2/GDP and 4.8 ton

CO2/person, whereas Germany had 0.2kgCO2/GDP and 9.8 tonCO2/person [13]. Germany is producing more economic output per emissions, however its population consumes more. Interestingly USA has the same 0.3 kgCO2/GDP as Argentina, but 17-ton Co2/person.

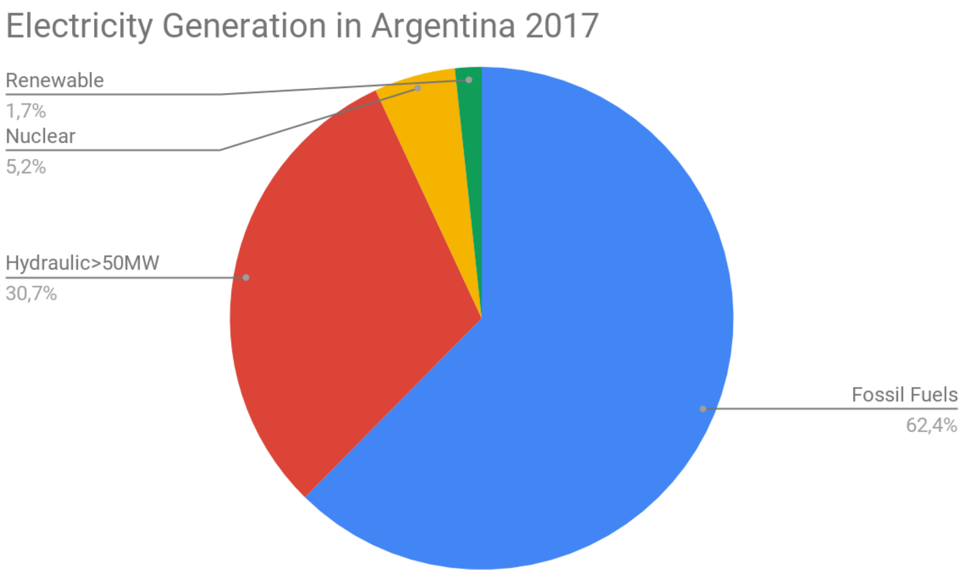


Fig.3 Electricity Generation in Argentina 2017,

Comisión Nacional de Energía Atómica [12]

1.3.1 Renewable Energy Policies in Argentina

The Renovar Program promotes investment in renewable energy generation. The objective is to achieve in 2025, 20% renewable in the energy generation mix. To achieve this, in 2020, 10 GW of new renewable generation power must be installed. The Program bids the generation of renewable energy and has already given in its first three rounds approx. 4500 MW and a new round is to come soon. Specifically, 1.142 MW, 1.281 MW and 2.043 MW, where awarded in each round. The average bid price was 54.72 USD/MWh, ranging from 61 USD/MWh in the first round to 51 USD/MWh in the final round.

The law 27.424 for distributed generations was enacted at the end of 2017, where every energy user can produce its own electricity and sell surplus energy to the system at a fixed price, which is given by the national energy distributor. Together with FODIS (Fondo Para la Generación Distribuida de Energías Renovables) the argentine regime is encouraging research, innovation and generation projects in renewable energy. According to the Law 27.191 for renewable energy, 15 Billion US will have to be invested to expand renewable energy capacities [12]. Fig.4 shows investments in the argentine electricity sector for the next 10 years. Hydroelectricity refers to plants over 50MW.

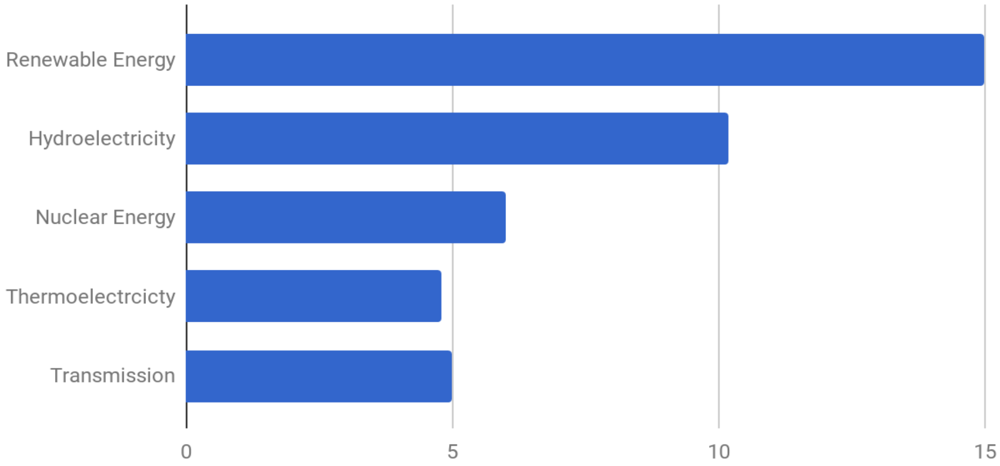


Fig. 4 Investment in the argentine electricity sector for the next 10 years, in Billions of US Dollars

Ministerio de Energía Argentina [12]

1.4 Renewable Energy Potential in Argentina

Argentina is rich in renewable energy. However, much of its generation capacity is in the north and south region of the country, where respectively solar irradiance and wind speed are high.

Firstly, in the NOA (north west Argentina) region the average solar irradiance is about 1.000 kW by square meter and with PV efficiencies of 12%, 2.200 kWh per square meter every year would be produced. As it can be seen from fig, 5, NOA region has one of the highest in the world with North Africa, Australia and Middle East.

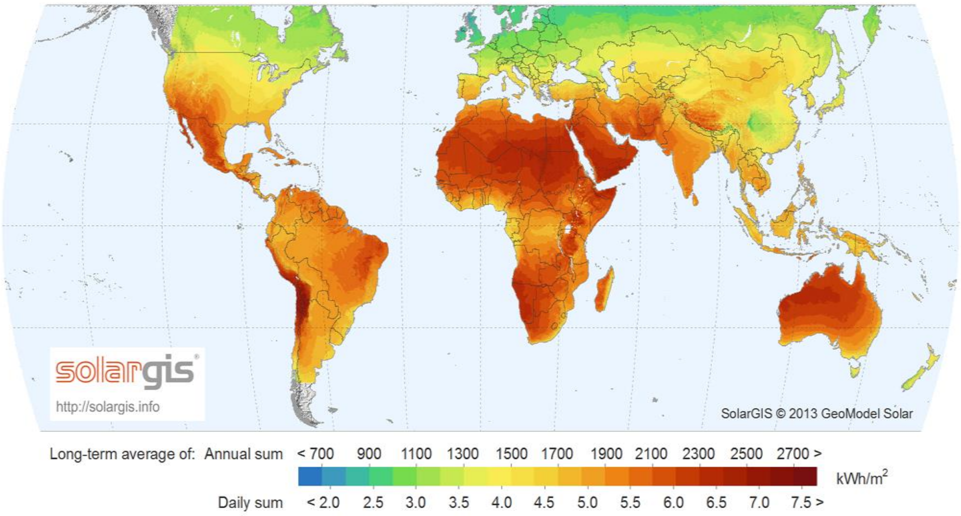


Fig.5, Global Solar Irradiance - EPIA European Photovoltaic Industry Association

Secondly, in 2009 NASA elaborated a global wind map and identified the main wind corridors. One of them is Tierra del Fuego, south of Argentina. Fig. 6 shows world regions and their average wind speed. South of Argentina has an average wind speed of 9 m/s, as it can be seen from the map.

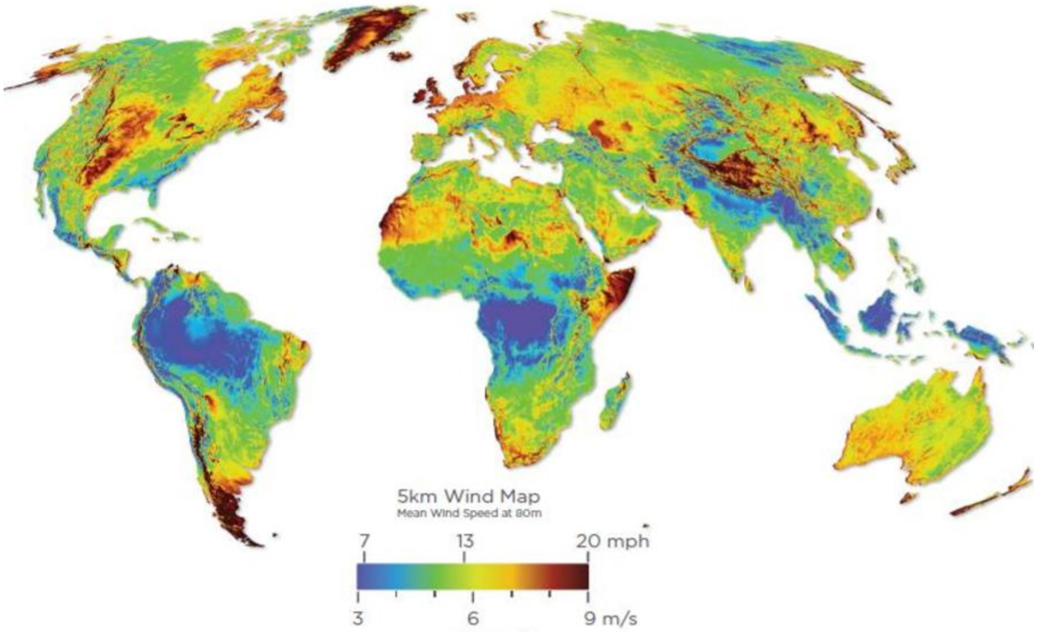


Fig. 6 Global Wind Map, NASA [14]

1.5 Relevance of clean energy supply at isolated places in Argentina

It is clear now, that Argentina has renewable energy potential. However, whereas its area is wide spread from north to south, its population is centered in the Region of Buenos Aires, Córdoba Entre Ríos and Santa Fe where 60% of the national electricity is used (fig.7 blue region). For that reason, transmission lines must be expanded to incorporate renewable energies in the electricity mix and to achieve the Renovar goals. In fig.8 the existing and new power transmission lines in Argentina are shown in red and in green respectively. 5 Billion US have to be invested to expand transmission lines through the country to achieve the renewable energy goal in 2025 [12].

This shortage in transmission lines, leaves hundreds of rural areas in off grid situation, which have to depend on other fuels as biomass or gas tanks for heating or cooking. In Argentina 12 million people use natural gas tanks or biomass as primary energy sources and in total 4 million natural gas tanks of 10 kg each are needed for supply at expensive costs, due to transport and fuel costs. Additionally, it is not an environmentally friendly nor a secure solution as gas is used inefficiently in households, which increases CO_2 emissions. However, if investments and incentives would be given, most of these off-grid regions could rely on renewable energies with storage technologies.

Fig. 7 Provinces with high energy consumption Argentina

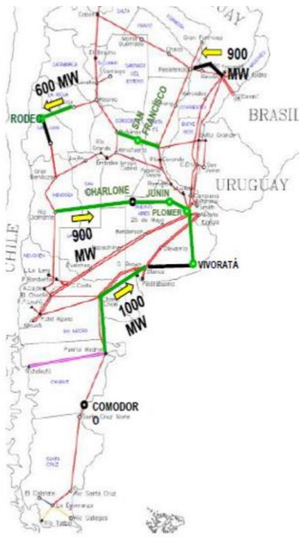


Fig. 8 Transmission lines, CAMMESA Cámara Argentina del Mercado Eléctrico

2. Concepts of electricity generation from wind energy

2.1 Wind generation and properties

Wind Energy has evolved from the application in extracting water from wells and making flour, to the generation of electricity.

Against fossil fuels, wind energy has both environmental and potential economic benefits. No pollutants are emitted, and it is completely emission free. Additionally, wind energy costs have been decreasing in the last years. In good wind sites the cost of electricity production from wind energy is comparable to fossil fuel-based energy generation and if taking into account greenhouse gas emission, even lower [15].

However, wind energy is not a solution for all the world energy problems. The main issues behind wind energy are wind variability, unpredictability and investment in energy transmission.

Wind is generated by uneven heating of the surface. The tropics receive a greater amount of radiation than the poles, which causes hot air to flow towards the poles. This air in motion causes low pressure at the tropics and cold air flows from higher altitudes towards the tropics. These events which cause air in motion, are to balance heat. [16]

As wind speed depend on season, topography and geography, there are better sites for wind energy generation. Wind speeds are generally higher near the coast and offshore as there are less objects to slow winds down (e.g. vegetation, buildings or mountains). Air in motion in contact with a rough ground is decelerated and turbulence is high. As altitude increases, the wind profile becomes laminar and faster, until an atmospheric boundary, where it becomes laminar (see fig.9 and fig.10). In higher altitudes, horizontal wind velocity increases, and more energy can be generated. One method to describe the relationship between velocity and height, is known as power law profile: [17]

$$\text{(e.1)} \quad \frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^y$$

v_i – wind speed at height i

h_i– height

y - wind shear

This approximation assumes that there is no slippage on the surface (wind speed is zero). Where *v* is the wind speed at each height, *h*. The exponent *y* is wind shear and is calculated by height and roughness length, z_0. [17]

$$(e.2) \quad y = ln(ln\frac{h_2}{z_0}/ln\frac{h_1}{z_0}) / ln(\frac{h_2}{h_1})$$

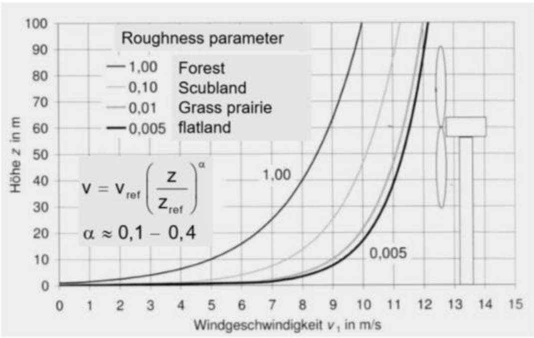


Fig.9 Earth boundary layer, influence of surface

Lecture in Wind- and Hydropower,

Prof. Dr.-Ing Martin Gabi, KIT

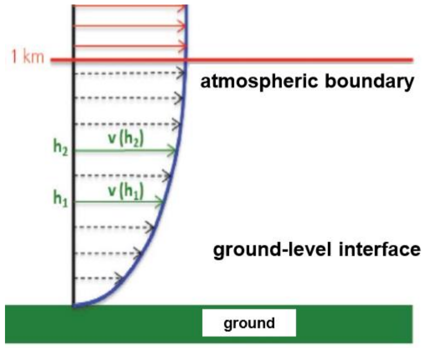


Fig.10, Power law profile, Lecture

in Fundamentals of Energy Technologies

Prof. Dr. Badea, KIT

Finally using (e.1) and (e.2), wind speed at h_i meters height can be estimated.

$$(e.3) \quad v(h_i) = v(h_0).\, ln\left(\frac{h_1}{z_0}\right) / ln(\frac{h_0}{z_0})$$

If wind speeds are too strong, structural problems can appear in the turbine or even be broken. For that reason, to secure the wind turbine, a switch off speed is set. Generally, 25m/s is the switch off speed, but strong wind turbines are switched off at 35m/s. Nominal speed for a wind turbine is set between 10m/s to 15m/s and switch on speed at 3m/s to 5m/s.

Wind speeds can vary throughout the day and year, causing intermittency issues for power grids. The most common probability density function to represent wind speed is Weibull.

$$(e.4) \quad p(v) = \frac{k}{A}\,.\frac{v^{k-1}}{A}\,.e^{-\frac{v^k}{A}}$$

Where v is wind speed, k is the shape factor, A is the scale factor. It has been observed, that wind speeds in most locations follow the Weibull distribution with shape factor equal to two, which is the Rayleigh distribution. Mean wind speed in a Rayleigh distribution can be expressed as a function of *A*. [2] Fig. 11 is the Rayleigh probability density function for different mean wind speeds (color lines). Sites with higher wind speeds have higher variability (see blue and green lines in fig. 11). This increases the difficulty in integrating wind energy as grid operators must manage more variability and only in high wind speed sites, projects are economically feasible.

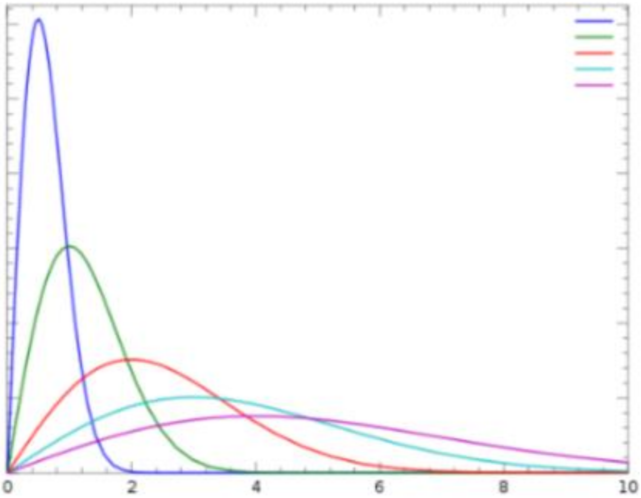


Fig. 11, Probability density function for different mean velocities

2.2 Wind Energy Production

Wind in our environment is converted to mechanical energy through a rotating impeller in a fluid machine, where impulse and angular momentum are exchanged. Wind turbines have several spinning blades, which are connected to an electric generator that produces electricity when the blades spin.

To calculate the annual wind energy production, wind speed probability density function is multiplied by the hours in which, each wind speed appears in a year. The value H_v gives the number of hours a certain wind speed appears. The annual energy production of wind energy can be calculated then as: [18]

$$(e.5) \qquad WE = \sum P_v . H_v$$

The product of the power output of every wind speed P_v and the hours during which each wind speed appears H_v, gives the wind energy production in that period. The power output values P_v compose the power curve of the wind turbine generator and are given by the turbine manufacturer.

The theoretical generated power P_{th} can be described by the following equation:

$$(e.6) \qquad P_{th} = W . v_r$$

W - air resistance in rotor blades

v_r - rotor Blade circunferencial velocity

$$(e.7) \quad W = 0{,}5.\ c_w\ \rho\ (v_1 - v_r)^2 F$$

F - area of blade

ρ - density of air

v_1 - undisturbed air speed

c_w - drag coefficient

The efficiency of an air turbine is the ratio of the power of the undisturbed air flow to the theoretical generated power by the turbine. If this theoretical efficiency is to be maximized, the blade velocity must be adjusted, with an optimal blade velocity of one third of the wind velocity, maximal efficiency of 59.3% (Betz's Law) can be achieved. The rotor efficiency must be taken into account as well to measure the global efficiency. Rotor efficiencies are generally between 70-75%, which gives a global maximum efficiency for a wind turbine of 40-44%. [17]

2.3 Wind Energy not a for all solution

Firstly, people do not like to live in areas with strong winds. For this reason, wind energy production is far away from population centers. This means, that wind energy must be transported, which requires transmission lines.

Secondly, wind energy production depends on wind conditions. It is only economically feasible in those areas, with good wind conditions and enough energy generation, that can justify the investment. Additionally, wind speeds variation is mostly unpredictable even more in sites with high winds. Wind speeds are also seasonal. If less wind energy is produced during winter, it means that for those months another generation capacity must be applied or that the wind park must be oversized in summer. Having more wind energy in summer is not a problem, if the grid is flexible to handle more variability. This forces grid operators to have generation capacity in case of grid disbalance. This back up capacity, makes the grid more expensive, as power generators are paid for the capacity to dispatch power.

Although renewable energies do not have fuel costs, wind energy curtailment can affect the revenue of wind energy project and it is becoming an important issue. When power plants cannot be shut down and power supply exceeds power demand, wind energy has to be curtailed to keep the grid safe. Transmission congestion may also cause curtailment. [19] Curtailment energy can vary from 0% to more than 15% of the total produced energy, depending on grid flexibility and wind variation. Wind energy curtailment is not per se a lost. If measurements are taken, wind energy curtailment can even be beneficial for the grid. Some wind farms achieve frequency reserves from curtailed wind [20].

This study investigates storage technologies to incorporate curtailed wind. Specifically, hydrogen technology. Although, this project, studies a case, it is the aim of this work, to replicate this model in a variety of applications.

3. Proposal for clean energy supply

3.1 Hydrogen as an Energy Carrier

The previous chapter mentioned problems in wind energy and the importance of storage technologies to back up wind variability and unpredictability. Wind energy is expected to grow in the coming years and due to its environmental benefits and power generation capacity, is key in achieving the Kyoto Protocol goals. By incorporating energy storage, grid operators will handle the system more efficiently and will create synergies that enhance renewable energy generation.

Additionally, wind energy curtailment affects wind project revenue. Storage technologies could make the project more economically feasible for the wind farm owner.

An interdisciplinary research program is being carried out at ITBA, to integrate technologies concerning production, storage and combustion of hydrogen, as clean fuel for electricity generation, automotive propulsion and industrial processes. Main challenges are the attainment of efficient self-pressurized alkaline electrolysers, innovative containers for hydrogen at high pressure, hydrogen clean combustion in Otto engines and stable power supply based on renewable energy sources.

This chapter will start with a brief description of Hydrogen and ITBA-KIT cooperation in research in this topic. Then give a technology proposal to store surplus energy from wind energy.

Free hydrogen practically does not exist in natural state. It can be produced either by reforming the hydrocarbon chains contained in natural gas, gasoline, fuel oil or coal, which are non-renewable resources, or by thermochemical processes of biomass or similar [21]. These processes, however, produce relevant amounts of greenhouse gases. Clean production of hydrogen using renewable resources is possible by dissociation of the water molecule in electrolytic reactors.

This study focuses in the process of producing Hydrogen from surplus wind energy by electrolysis. Peak energy can be used to fill periods when wind drops.

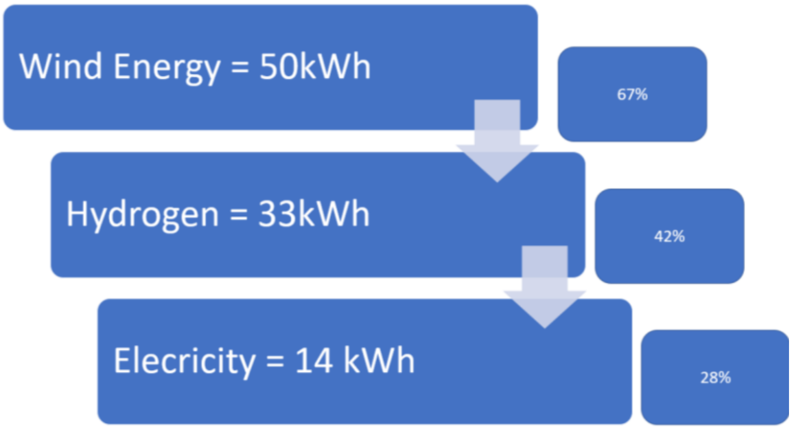
Hydrogen as an energy carrier presents advantages. Firstly, hydrogen technology is already applied in the chemical industry for decades and its risks and security protocols are well known. Secondly, hydrogen is well suited for seasonal energy storage without energy losses over time. There are no electrolysers specifically designed for operation with wind turbines, but the rapid response of electrolysis to power variations, makes them suitable to work with wind turbines and other renewable energies.

Hydrogen production from wind energy has not been implemented in large scale wind farms yet, mainly due to large capital costs. However, technology is fast growing, and prices are predicted to decrease in the years to come. [22]

Hydrogen is proposed as the energy storage system referred to above, because it can be produced and stored at high pressure, by using intermittent energy surplus, and can be used as clean fuel to generate stable electricity, when renewable sources do not meet power demand.

3.2 Hydrogen Energy System

The following chart is the proposed wind hydrogen energy system. Wind energy curtailed is used for producing hydrogen by electrolysis which then in an internal combustion engine is converted to electric energy. Although this process has an overall efficiency of only 28%, it only uses curtailed wind energy, which if not applied for producing hydrogen, would be disposed.



For large scale renewable power integration, long term energy storage is required. Production levels of renewables vary significantly between seasons. In short term balancing can be accomplished by demand side management and batteries, but for long term storage hydrogen is better suited [23].

There are a wide range of options for energy storage and, depending on requirements, different technologies are better suited. Nevertheless, a general comparison of different storage options is out of the focus of this study. Storage technologies for long discharge time are interesting in this study and hydrogen technology is the option of choice.

Fig.13 gives storage technologies according to their discharge duration and power capacity. An interesting alternative to hydrogen storage is compressed air energy storage (CAES), which improves the efficiency of fossil fuel power plants as gas turbines. However, such storage technology depends on further utilization of fossil fuels as gas or diesel. For this reason, this project will not study further this technology and will focus on hydrogen technology for energy storage.

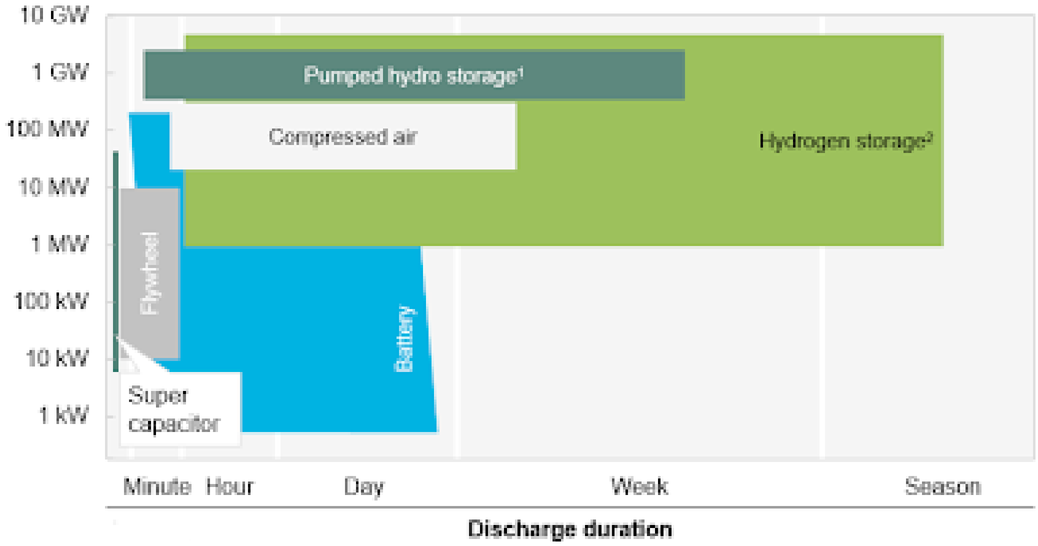


Fig.13 Technology overview in power and time,
IEA Energy Technology Roadmap Hydrogen and Fuel Cell [14]

Hydrogen is exceptionally well suited to storage large amounts of energy for long durations [23]. As it can be seen, hydrogen has the longest discharge time and greatest power capacity.

Hydrogen storage is then adequate for seasonal energy storage. As wind vary through season, energy shortcut may be only in winter, for that reason having a long discharge time technology is important to be able to use that surplus energy from summer in winter.

Fig.14, wind energy generation and two different power loads are plotted. First, when wind energy exceeds power load (orange) surplus energy can be stored by producing hydrogen. Secondly, hydrogen is applied to fill gaps of energy, when wind energy is less than power load (grey). This process has several losses, due to the inefficiencies in the production process of hydrogen. However, the energy necessary for the production process is energy curtailed, due to grid limitations to handle wind energy variability.

The net effect of incorporating hydrogen storage in intermittent power resources makes the power generation more predictable and less variable.

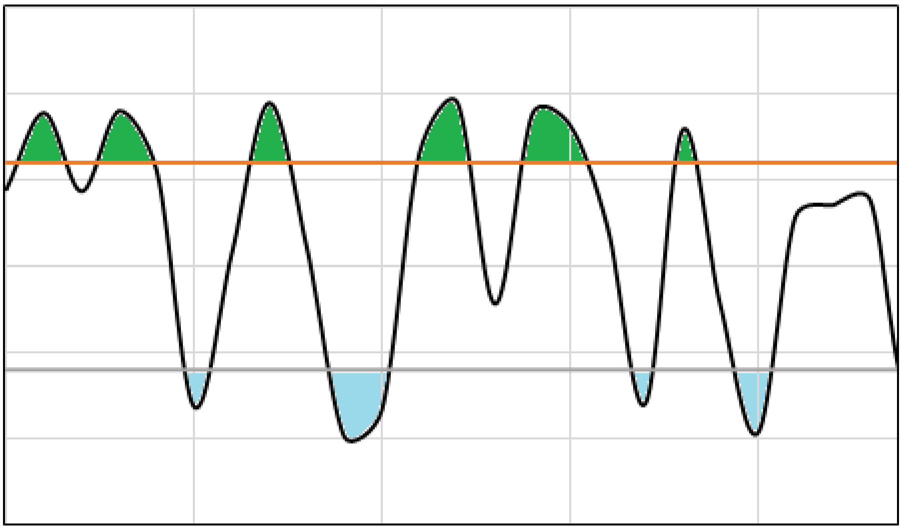


Fig.14 Hydrogen Storage applied in renewable energy generation

But, how much storage capacity is needed for long term storage when renewable energy production increases. Studies have shown an exponential increase of demand for long term storage when renewable energy share of 60% to 70%, see fig.15 [24]. Germany is planning to have 80% to 90% renewable electricity. With that energy mix, it is expected around 15% of the total energy to go into the hydrogen production [23]. If no long term energy storage is applied, thermal power plants would be needed to provide back up and grid security, which increases grid costs and makes the energy system inefficient.

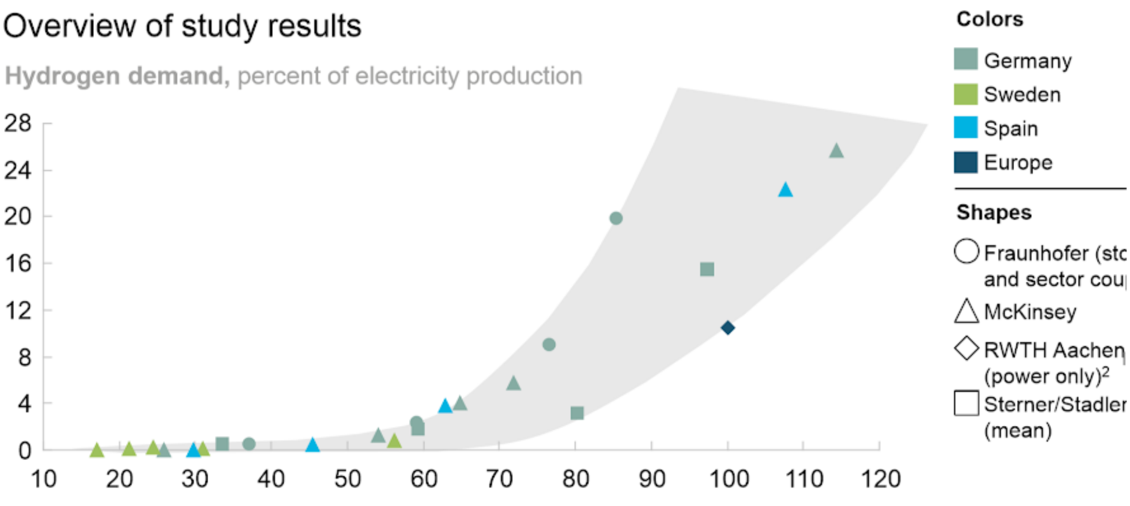


Fig. 15, The need for hydrogen storage increases exponentially with the variable renewable energy share, ISE, 2017; BMW; RWTH Aachen; Sterner and Stadler (2014); McKinsey [25]

Apart from storing power during periods of peak renewable power generation, hydrogen can be used when there are no enough renewable capacities for peak demand. Japan, South Korea and Taiwan for example are already importing hydrogen to generate clean energy [23]. This gives countries, with renewable energy potential and surplus clean energy, significant commercial and economic opportunities. Additionally, Hydrogen is easily adapted to existing power grids.

Hydrogen can be up to 5 to 20% of the mixture, depending on the natural gas pipeline and gas chemical composition. [24] Natural gas power plants and combustion engines can be retrofitted to use hydrogen as fuel without major costs.

3.3 Storage of renewable energy surplus as electrolytic hydrogen

Most of the commercially available electrolysers operate at 1-30 bar, which requires subsequent use of compressors to obtain hydrogen stored at 700 bar or more. Although low pressure electrolyser are relatively simple and cheap, the further compression of the gas requires additional expensive equipment and consumes up to 50% of the stored energy, which drastically reduces the energy efficiency of the whole process. To overcome this limitation, ITBA has developed the technology of self-pressurized alkaline electrolysers, to produce and store Hydrogen at high pressures, without using compressors.

ITBA has done research in the field of electrolysis since 2005, where different prototypes have been designed. The next step is to develop a robust self-pressurized electrolyser prototype for applied power of 50 kW, to produce 1kgH2/h at 400-500 bar. Furthermore, this prototype could be sized up to 350 kW and produce 5-7kgH2/h at 400-500 bar.

3.4 Innovative tanks to store hydrogen at high pressure

In comparison to all other gaseous fuels, hydrogen has higher specific energy but lowest density, hydrogen high pressure storage is required to have equivalent energies in reduced volumes. ITBA has developed a new concept of tank for high pressure gas, consisting on a coiled long tube of small diameter.

Regarding conventional storage units, this innovative container has several benefits: lower weight, reduced cost, higher safety and unrestricted shape. Weight and cost reduction are achieved by extruding long, thin tubes made from high tech aluminum alloy, which preclude corrosion and hydrogen embrittlement, enabling a long service life. The manufacturing process is cheaper than the required to produce conventional tanks of large diameter and thick wall, made from steel or composite materials.

The increased safety is intrinsically related to the high resistance to inner pressure of tubes with small inner diameter. Additional safety is added by the winding design, because of the enhanced heat transfer capacity. Moreover, if one or several spirals are damaged (due to material failure, external impact or similar), the high flow impedance inside the coil will determine a gradual liberation of gas, which prevents a sudden expansion wave.

Finally, the size and shape of the tank can be modified by winding longer tubes or connecting several coil units. This enables a modular system to fit the geometry designed for each application, which extends the range of uses of these tanks, including hydrogen powered vehicles.

Key technical issues are associated with long term operation and charge-discharge fatigue of the storage unit, as they cannot be properly tested in a laboratory environment.

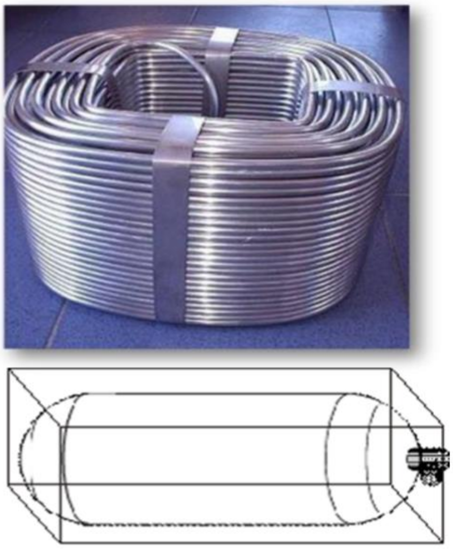


Fig. 16 ITBA innovative tanks for high pressure hydrogen

ITBA has constructed and designed various coiled tanks for up to 25 kg hydrogen at 700 bar. Hydraulic charge discharge tests up to 1050 bar, have been repeated without registering material fatigue.

ITBA prototype:

- Material Al 6063 T6
- Tube length 200 m
- Inner diameter 5 mm
- Empty weight 27 kg
- Storage capacity 2,7 Nm3 at 700 bar
- Hydraulic test 1050 bar

3.5 Internal combustion generator fueled with hydrogen

To develop the hydrogen technology for clean and cheap electricity generators, ITBA has established a R&D group dedicated to the study, design and optimization of gaseous fueled Otto engines. The combustion properties of hydrogen make it an attractive alternative to gasoline [21]. Its broad flammability limits and relatively high-octane number can be used to improve the efficiency of Otto engines, by using higher compression ratios and lean burn operation.

A hydrogen lean burn engine could result in:

- Higher engine brake thermal efficiency due to:
  − Combustion gas properties resemble those of air → approximation to ideal cycle
  − Less fuel throttling → lower pumping losses
  − Lower combustion temperatures → lower heat losses
  − Air fuel mixture less prone to auto ignition → higher compression ratio
- Guaranteed zero tank to wheel emissions → low combustion temperatures stop the formation of NOx
- Low acoustic pollution → no diesel knock + constant operating condition
- Lower embedded costs than alternative zero emission power units → fuel cells and fully electric

3.6 Off grid electricity supply

Stable electricity supply, based on renewable energy sources, could be achieved by proper integration of wind and solar energy with all the hydrogen technologies described above. The challenge is to assemble them into a robust, reliable and cost-convenient system. The design and construction of an installation is proposed, including wind generator, PV solar panels, electrolyser, hydrogen storage, gas engine, batteries, electrical grid and control system, to be studied experimentally as a pilot plant suitable to be reproduced in scale. Important is a modular design of components possible to be serviced and repaired by local technicians in weak infrastructure environments. Minor problems, such as failure of individual components may not lead to a long-term system failure.

The modular design and the clear definition of interfaces are of major importance, to enable the integration and testing of future new or improved components. Main topics of the research and development plan are:

• Optimization of robust and simple wind turbines, suitable for the regional high wind speeds

• Optimization of alkaline self-pressurized electrolysers, to fit specific needs.

• Development of efficient coiled storage containers

• Adaptation of a conventional gas engines to run with hydrogen, biogas, natural gas or mixtures of them.

• Modeling of the overall system

• Development of a robust and simple control and regulation technology.

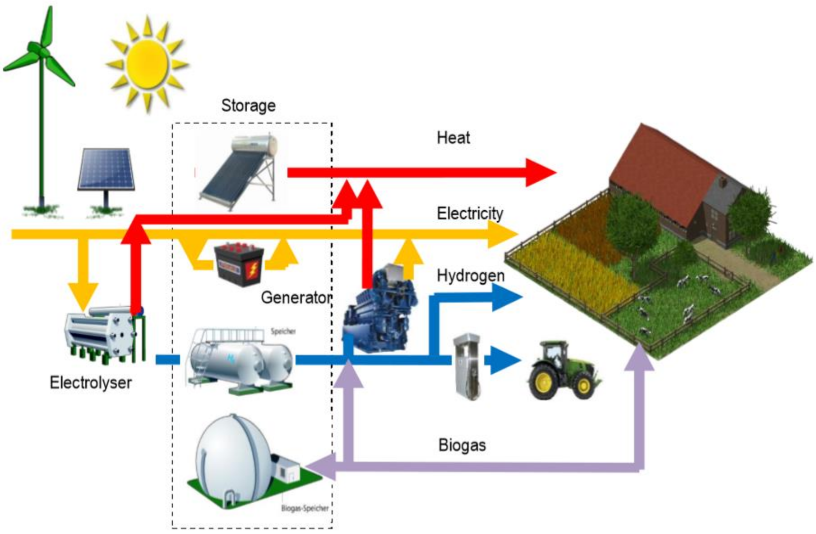


Fig.17 Grid based on renewable energy, scheme from KIT

4. Isolated place in Argentina as a case study

4.1 Application study in Río Grande

The aim of the project is to study the incorporation of hydrogen as a storage technology for surplus wind energy at isolated places. Generally, isolated places use diesel or natural gas as baseline and peak energy generation. These are expensive fuels and are used at varying operating points at lower efficiencies, which increases CO2 emissions.

In Argentina, as in other countries, renewable energies have priority dispatch. When wind speeds are high and energy productions peaks, other flexible energy sources are decreased. However, changing thermal power plants from its nominal power rate, decreases efficiencies and forces grid operators to count on other generation capacities in case of grid disbalance or wind speed drop.

This chapter will describe the energy matrix used today in Rio Grande and assess Rio Grande wind energy potential. To simulate surplus energy, this project fixed gas turbine to work at top efficiency and applied wind energy and hydrogen technology to balance peak demand. It is the aim of this work, that this studies approach is useful for other applications.

Río Grande is situated in the province of Tierra del Fuego, at the south extreme of Argentina, with a population of approx. 80.000 inhabitants.

Río Grande was selected as an application study, due to its vast renewable energy potential. Although the south of Argentina has one of the best conditions for wind energy production, it uses expensive power resources. In general, energy islands or microgrids, depend on expensive energy sources and inefficient power plants, due to access and investment limitations.

Fig. 20, Río Grande location in Tierra del Fuego Province

Tierra del Fuego has the most expensive energy costs in Argentina. In 2017, their costs where of 105U$/MWh (without taxes), almost four time more than in Buenos Aires. Urgent energy policies and investment are to be made, considering wind conditions in the region.

4.1.1 Energy load in Río Grande

To determine Río Grande power demand, information from CAMMESA (Compañía Administradora del Mercado Mayorista Eléctrico [26]) for the Patagonian region was taken as both, Río Grande and Patagonia in general, share inhabitants' habits. Patagonia data concerning ALUAR industrial plant were extracted, because they are not representative of Rio Grande. This data was scaled to Rio Grande, by using their max and min loads. As a result, total power demand for every hour in Río Grande was estimated. The next graph shows, energy demand in Río Grande along the 12 months in 2017.

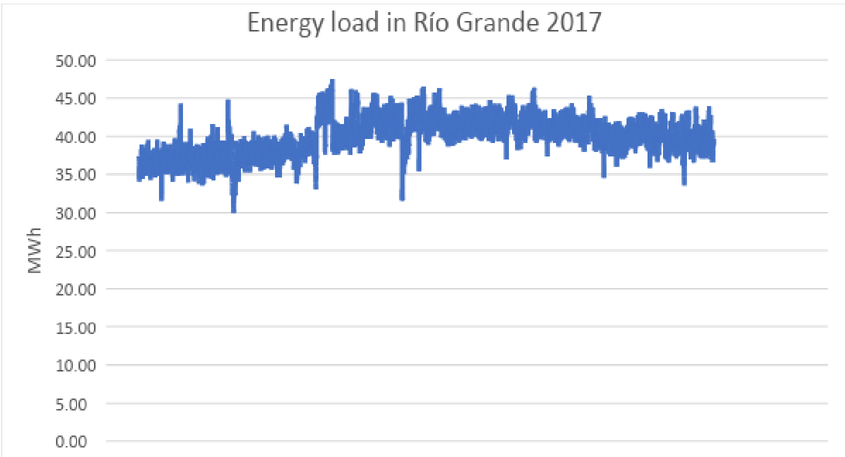


Fig. 21 Energy load in Río Grande in 2017

In general, the load pattern in Río Grande is smooth. Both, season variation and load range are minor. In 2017, the maximum load was of 47,50 MW, minimum load 30MW and 40 MW on average.

4.1.2 Present power generation in Río Grande

Río Grande relies on expensive power generation sources and has the following power generation mix:

Type	Fuel	Power (kW)	Note
MAN G8V 30-45 ATDG	Diesel	750	Black Start
CUMMINS/SULLAIR	Diesel	1.200	Black Start

FIAT TG 16	Gas	16.000	Cold Generation
FIAT TG 16	Gas	15.000	Cold Generation
LM 2500 GE	Gas	20.000	Base
LM 2500 GE	Gas	28.800	Base

Table 1 Power Generation capacity in Río Grande in 2018

Table 1 shows present power generation in Rio Grande. As it can be seen, the energy matrix relies on peak generating power plants as gas. This power generation plants, have high flexibility, but use expensive fuels. Generally, this power plants are used for peak generation, due to their power rates that can balance peak load variations. But these are for base power generation expensive and inefficient.

4.2 Assessment of wind energy potential in Río Grande

Wind speed were estimated Estaat 70 meters height, with real wind conditions taken from Estación Astronómica Río Grande at 10 meters height. The data collected is available at Windguru [27]. Wind speeds were recorded by an accelerometer at 10m height. The database included winds from July 2017 to July 2018, which were used to estimate one year wind speeds.

Fig. 22 Wind measurement location, Windguru [27]

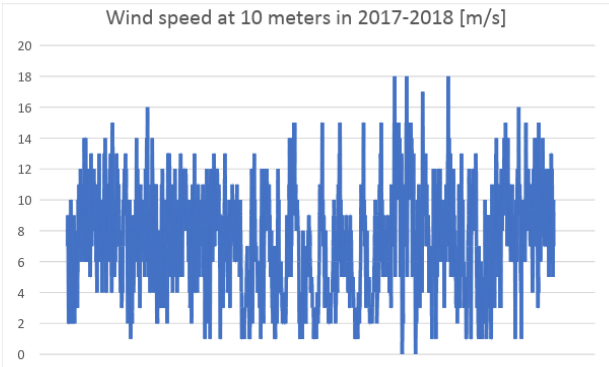


Fig. 23 Wind speed at 10 meters during one year [3]

Wind speeds at 10 meters height were projected to 70 meters using the approximation mentioned in chapter 3. Wind speeds at 70 meters height can be estimated by equation e.3. The roughness length was estimated at 0.03 meters, which is for open agricultural areas without fences and hedgerows and soft rounded hills. [16]

$$v(70m) = v(10m).\,ln\left(\frac{70}{z_0}\right)\ /\ ln\left(\frac{10}{z_0}\right)$$

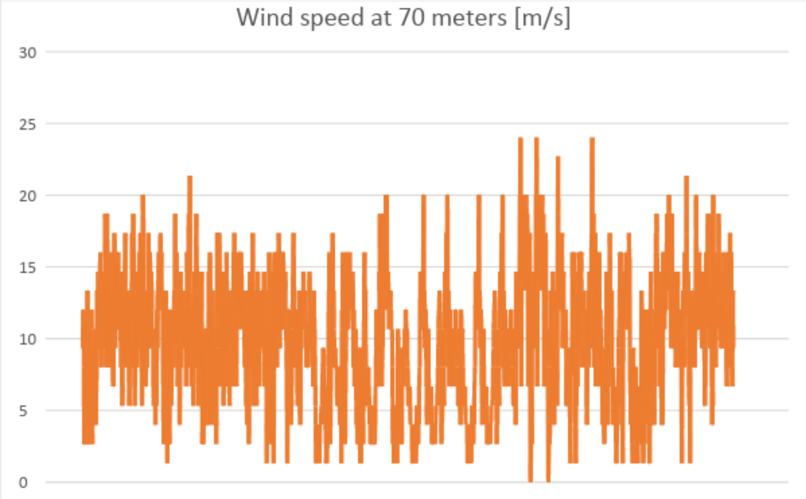


Fig. 24 Wind speed estimation at 70 meters

The next histogram is the annual distribution of wind speeds by number of hours at 10 meters height. Average speed is nearly 7.38 m/s at 10 meters height and indicates great wind conditions.

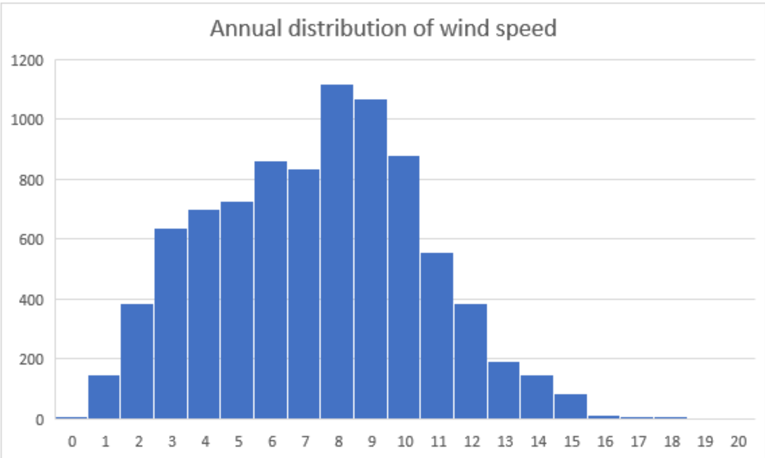


Fig 25. Annual distribution of wind speed in Río Grande at 10 meters height

4.2.1 Wind energy production

For every wind speed value, from cut in to cut out, the product of the power output and the time during which the speed value appears in a year is calculated. The sum of the products is the annual energy production, WE. The power output values, which compose the power curve of a wind turbine generator, are provided by the turbine manufacturer.

$$WE = \sum P_v . H_v$$

Wind farm design is not straightforward, and the optimal selections of wind turbines is out of the focus of this study. A project situated in Cabo Domingo, 10 km away from Rio Grande is taken. The Project was studied by Secretaría de Desarrollo e Inversiones, Gobierno de Tierra del Fuego. [28]

The selected wind turbines are from national companies, NRG Patagonia and IMPSA. Both of 1500 KW. The models are NRGP 64-1500 and IWP 70-1500. The wind farm has one NRGP 65-1500 and two IWP 70-1500. Both power curves are shown next.

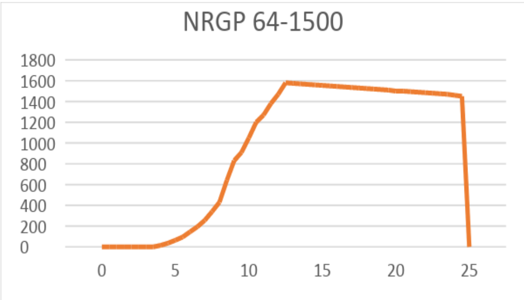


Fig.26 Power Curve NRGP 64-1500, [29]

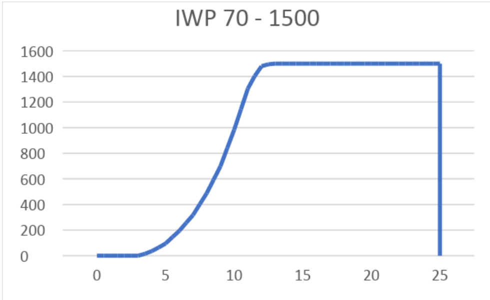


Fig.27 Power curve IWP 70-1500, [30]

The wind turbine generator starts to produce power at the cut in speed. Within a specific range after this, the power increases exponentially till it reaches the nominal value. The velocity of the rotor remains with no variation at all wind speed values, until the cut-out speed. At this speed, the turbine suspends its operation for safety reasons and wind energy production falls.

The ratio of the net electricity generated, to the energy that could have been generated at continuous full power operation is the capacity factor. Capacity factor is a general indicator of wind conditions and wind turbine selection. A site on which a wind power plant shows annual capacity factor over 30% can be considered as a site of high wind potential and appropriate for wind energy production.

(e.8) $Capacity\ Factor\ =\ Energy\ Output\ /\ Installed\ Capacity$

At Cabo Domingo, capacity factors of 59% and 57% for both types of generators are achieved.

kWh	Energy Output	Installed Capacity	Capacity Factor
NRGP	7.708.527	13.140.000	0,59
IWP	7.550.922	13.140.000	0,57

Table 2 Wind park energy output, capacity installed and capacity factor

4.3 Total energy generation

Total energy generation is estimated by adding wind energy production to existing gas turbines. Río Grande uses peak power generators (gas turbines) for base and peak power generation.

In this application study, two gas turbines will work approx. ¾ of their full load at more efficient operating points for base load. Peak load will be balanced with wind energy and hydrogen storage. As it will be discussed at the end of this chapter, gas turbines emissions are related to the operating point. By increasing gas turbines load, emissions are reduced exponentially.

Fig. 28 shows power generation from gas turbines and wind turbines (base and peak power production). Base load generation must vary between seasons. In winter wind energy drops and energy demand increases. As seen in the figure, base generation increases to approx. 80% full load in winter to match load variation.

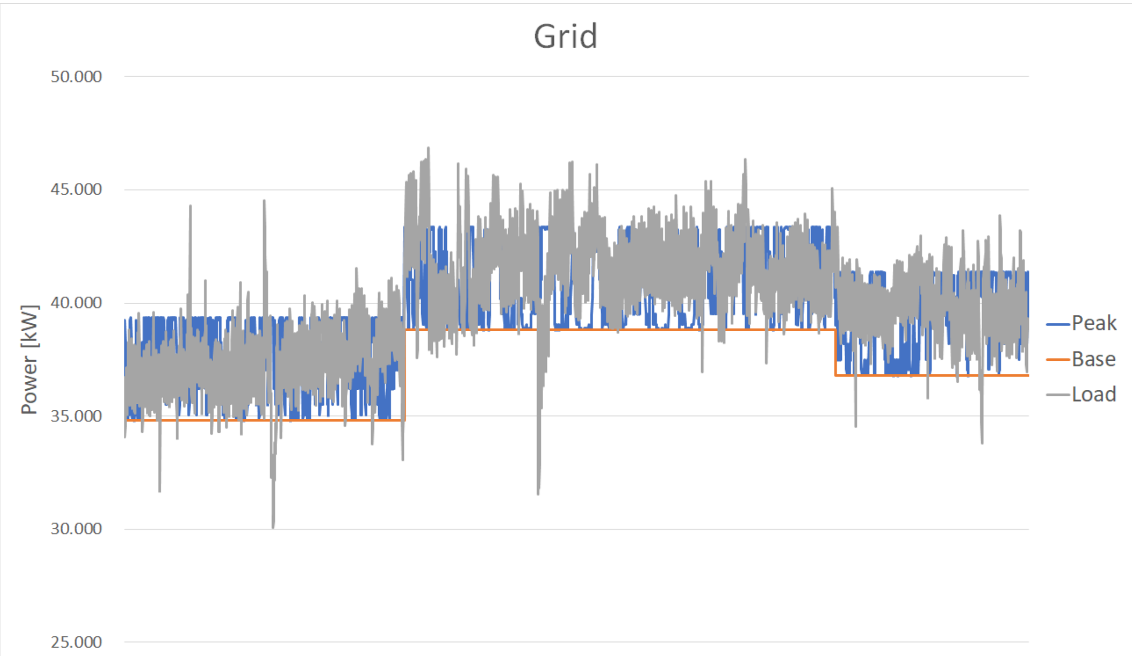


Fig. 28 Energy production and load variation in one year

4.4 Surplus Energy for Hydrogen Production

By comparing both power curves, load and generation, power surplus can be measured. This surplus, in conventional wind farms must be curtailed to balance the exceeding power generation and safeguard the grid. However, in this case, power surplus can be used for hydrogen production, and energy can be stored and used when necessary.

Wind and load variations produce different surplus at every hour. Wind in winter is lower than in summer and power demand is higher in winter. The following figure shows energy surplus in one year:

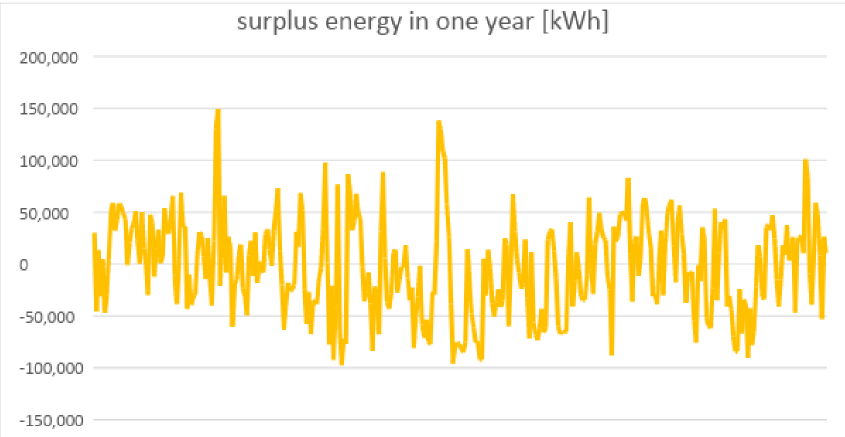


Fig. 29, surplus energy estimation in one year

4.4.1 Hydrogen Production

ITBA electrolyser can work with varying power input. Additionally, working at higher pressures increases the efficiency. As it can be seen from fig.30, storage efficiency increases with pressure.

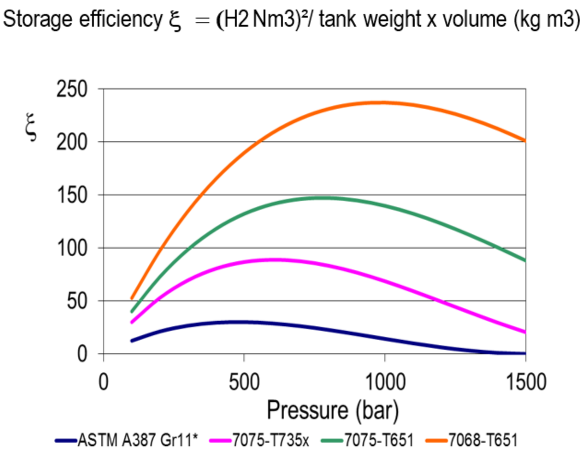


Fig. 30 Storage Efficiency vs pressure

The application study assumes a commercial equipment at 500 bar and 400 kW power input electrolyser. This equipment would produce with the performance indicated in the Table 3, 8 kgH2 per hour.

Lab-Electrolyser		
Power Input [kW]	H2 [kg/hs]	Pressure [bar]
50	1	400

Table 3 Extrapolation from ITBA Lab Electrolyser [34]

The definition of the number of electrolysers is, due to the nature of the problem, not straightforward. The selection of the total number was made considering wind energy generation and hydrogen production costs. Also, the capacity of one internal combustion engine of 250 kW which is used to generate electricity from hydrogen.

Simulation were run with different numbers of electrolysers and both CO2 emission reduction and net present value where measured. The results of the simulations can be seen in fig. 31. The best use of the surplus energy is made, when max CO2 emissions are reduced and from an economical point of view, the highest net present value is achieved. In the next chapter, the cash flow of the project will be presented with the net present value estimation.

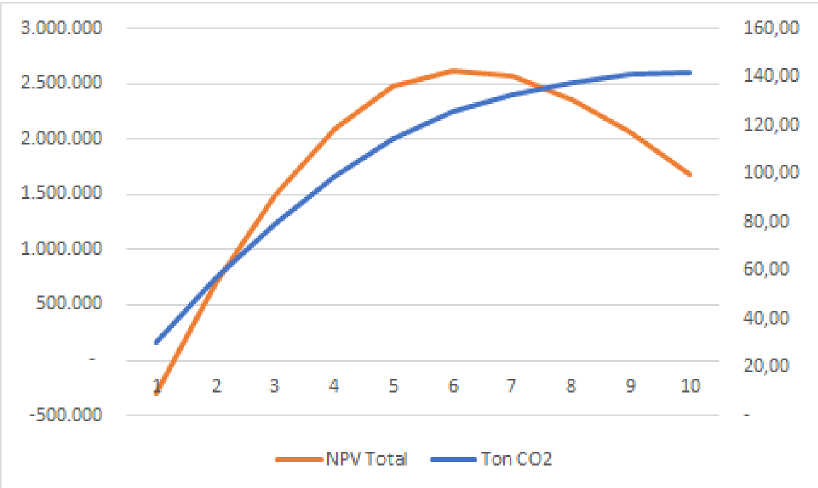


Fig. 31 Total Net Present Value and ton CO2 reduced by increasing the number of electrolysers

As it can be seen from fig. 31, the number of electrolysers increases the amount of CO2 reduced. But, this marginal increment decreases with the number of electrolysers added. By having more electrolysers ready to produce hydrogen, less wind energy is curtailed. However, the more equipment's are added, more investment is made. As wind speed is variable, electrolysers will not be operational fully and their capital expenditures will not be covered by the hydrogen they can produce.

This simulation was made for a fixed and exceeding hydrogen storage capacity of 3500 kg to measure full effect of marginal increase in hydrogen production.

The next chapter will simulate both variables to find the economic optimal point between storage and production capacity.

4.4.2 Hydrogen Storage

Fig. 32 is a histogram of the number of days certain hydrogen production in kg is reached. In winter, wind speeds drop and power demand increases, leaving 70 days in which no hydrogen can be produced. Hydrogen production peak values are only reached during summer, when wind speeds are high and power demand drops.

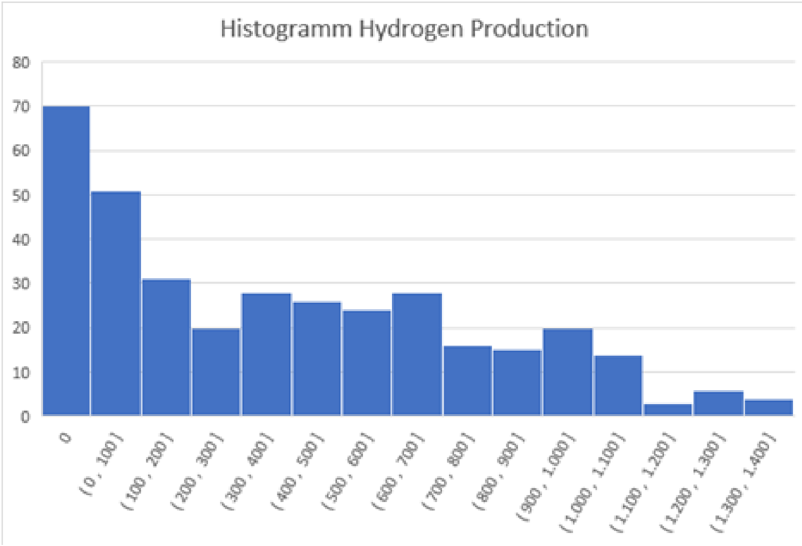


Fig. 32 Number of days in one year vs. kg of Hydrogen produced

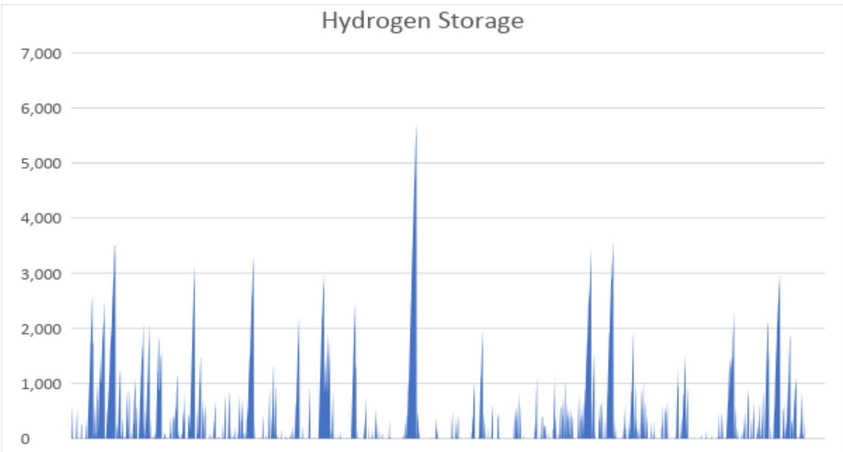


Fig. 33 Hydrogen stored (kg) along one year

Fig. 33 shows the amount of hydrogen that is left in the storage tanks in one year. As it can be seen, hydrogen is consumed fast. This is because, when available, hydrogen is used for peak load instead of gas fuel. This net effect can be seen in fig.14.

When wind energy exceeds power demand, these peaks are used for hydrogen storage. When power is missing this produced hydrogen is applied for power generation. The net effect reduces variability in wind energy generation.

ITBA coiled tanks could be constructed at any size. A modular design is reasonable to expand storage capacity if the wind park is expanded. Tanks of 100 kg capacity are to be used as a modular design. The total capacity will be defined by an economic analysis and simulation between the number of electrolysers and storage capacity, see next chapter.

4.4.3 Hydrogen to electricity

ITBA has recognized expertise in conversion of Diesel to Otto engines. For example, in 2017, an original Bus engine was converted to Otto engine fueled with gaseous hydrogen, in view to generate electricity on board, to be stored in batteries feeding two regenerative electric motors able to power the bus and to gain break energy. It is ready for tests on dynamometer.

Combustion properties of hydrogen, like high octane number and broad flammability limits, allow higher compression ratios and lean burn operation, which improves the engine efficiency. A hydrogen lean burn engine could result in:

- Higher engine thermal efficiency due to:
  - Combustion gas properties resembling those of air → approximation to the ideal cycle
  - Less fuel throttling → lower pumping losses
  - Lower combustion temperatures → lower heat losses
  - Air fuel mixture → less prone to auto ignition → higher compression ratio
- Guaranteed zero tank to wheel emissions, because low combustion temperatures stop the NOx
- Low acoustic pollution due to constant operating condition and no diesel knock.
- Lower embedded costs than the alternative zero emission power units: fuel cells and fully electric.

Let’s assume a diesel internal combustion engine of 250 kW converted to Otto cycle to work with hydrogen. At nominal power, 18 kg of hydrogen would be needed every hour. With the total amount of hydrogen produced, 1090 ton per year, the internal combustion engine would be in operation 8.012 hours.

4.5 Emission reduction by partial replacement of fossil fuels

Gas turbine generally are low emitter of pollutant as CO, UHC (unburned Hydrocarbons) and NOx, because fuel is combusted with ample excess of air to ensure complete combustion.

But during minimum load and ignition pollutants and CO_2 emissions vary. Nitrogen oxides, SOx and particulates formation can be limited by fuel and will not be analyzed in this chapter. Estimations will be based on Río Grande base load gas turbine.

Producer	GE
Net Output	23.1 MW
Net Efficiency	33,20 %
CO at 15% O2	25 ppm
NOx at 15% O2	15 ppm

Table 4 Product Specification, General Electric

4.5.1 Exhaust Gas

Gas turbine emissions can be separated in major species (CO_2, N_2, H_2O and O_2) and pollutants (CO, UHC, NOx, SOx). Emissions are shown in the table for a typical gas turbine.

Major Species	Typical Concentration [%]
N2	65 – 72
O2	12 – 18
CO2	1 – 5
H2O	1 – 5
Pollutants	PPMV
NO	20 – 220
NO2	2 – 20
CO	5 – 330
SO2	Trace – 100
SO3	Trace – 4
UHC	5 – 300
Particulate	Trace – 25

Table 5 Gas turbine exhaust emissions, Gas turbine Emission Control, General Electric [31]

4.5.2 Carbon Oxides and UHC

Carbon monoxide and UHC are formed at low combustion efficiencies. At ignition and acceleration, their emissions are higher. In very low operating conditions CO and UHC emissions increase quickly. These characteristic curves are of a typical heavy-duty machine series.

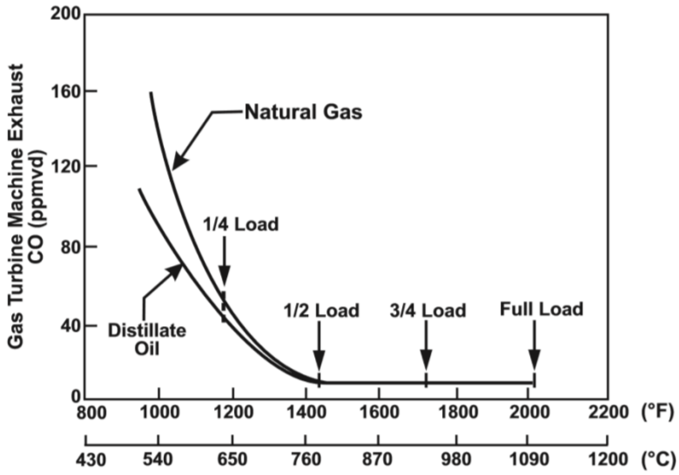


Fig. 34, CO emission at varying load, Gas Turbine Emission and Control, General Electric [31]

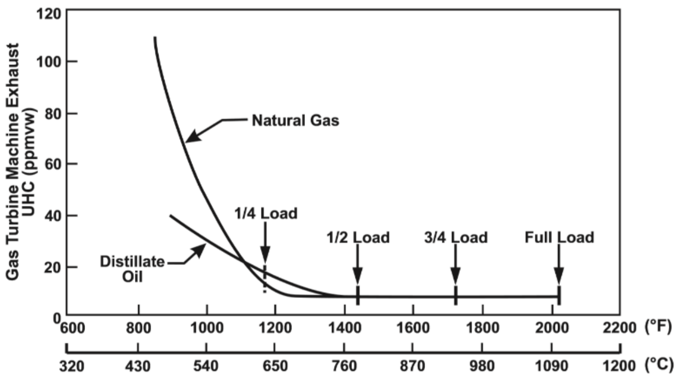


Fig. 35, UHC emission at varying load, Gas Turbine Emission and Control General Electric [31]

4.5.3 Nitrogen Oxides

Nitrogen oxides (NO and NO2) are formed by the oxidation of free Nitrogen in the combustion air or fuel and are mainly a function of the stoichiometric mixture and temperature.

From the figures above, it can be concluded that, working at full load is more efficient. However, NOX emissions due to their formation, vary opposite, both in internal combustion engines (ICE) and in turbines, see fig. 36. This means that, at lower NOx emissions other exhaust emissions are not affected. Gas turbines are equipped today with applications to reduce NOx formation.

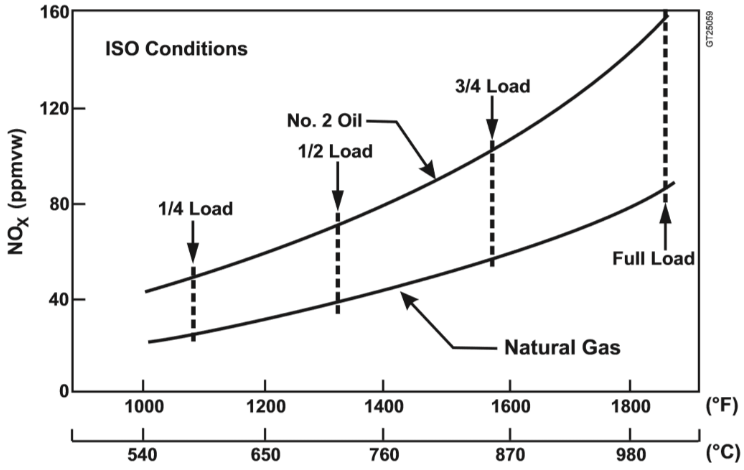


Fig. 36, NOx emission at varying load, Gas Turbine Emission and Control, General Electric

4.6 Gas Turbine and Hydrogen ICE

Hydrogen against gas, has no carbon in its molecule and its exhaust gas has no carbon oxide formation. However, Nitrogen oxides are present at hydrogen ICE and as shown in the table even higher. The table gives NOx emission at fixed temperature and full load relative to gas fuel.

Fuel	NOx [ppmv/ppmv] from CH4]
CH4	1
Oil	1.57
Hydrogen	4

Table 6. Relative NOx emission, Gas Turbine Emission and Control General Electric [31]

In a Hydrogen ICE there is no tradeoff between CO and NOx formation, and NOx emissions can be set to minimum, by regulating the temperature and design together with refrigeration.

4.7 Emission Estimation

Emissions are estimated based on full load efficiencies. As shown before, exhaust gas emissions are higher at other operating points. However, a calculation of this effect is out of the focus of this study and should be analyzed apart. This effect of varying operating point is not estimated but operating far from full load increases 4 to 6 times exhaust gas emissions as it can be seen in the fig. 34 and fig. 35.

The following equation is the complete combustion of natural gas:

$$CH4 + 2O2 -> \ CO2 + 2H20$$

As a total combustion is estimated, CO formation is zero. One TJ of CH_4 produces 56.1 ton CO_2 [31] or 201.96 ton CO_2 are produced per MWh. [32]

By using hydrogen storage technology, CH_4 consumption is reduced and for that reason less CO_2 is emitted. The Hydrogen ICE produces 1.902 MWh per year. Using the gas turbine efficiency and IHV of the gas a total of 384.128 ton of CO_2 are reduced.

Emission reductions due to wind energy generation can be estimated as well. A total of 22.430 MWh is produced per year. This amount of energy in a gas turbine of 34 % efficiency would account to 4.530.000 ton CO_2 per year.

To this total amount of reduced CO_2, the effect of operating the gas turbine always at full load should be included.

5. Economical and financial feasibility of the project

5.1 Economic and Financial Model

An economic and financial model is proposed in this chapter to analyze alternatives and scenarios in which the project could be optimized.

The model is integrated by the following key aspects:

- Revenue
- Capital costs
- Operating costs

Wind energy projects are capital intensive, with large amounts of investment, no raw material costs, generally tax incentives and small operation costs.

$$R(i) = p(i) * e(i)$$

$R(i)$ – revenue in period *i*

$p(i)$ – total price in period *i*

$e(i)$ – energy production in period *i*

Income is mainly from the sale of energy. However, other revenue streams as energy credits or carbon credits and tax credits exist.

5.1.1 Energy Pricing

Energy prices can be arranged by the following options:

- Power Purchase Agreement (PPA)
- Market Based Pricing
- Feed in Tariff (FiT)

In a PPA model the prices for power have a take or pay structure. The utility must take all energy that is produced, regardless of the demand for energy.

Market based pricing are not long term as PPA. Prices are set according to the spot market.

Argentina applies with the Renovar Program, FiT. Feed in Tariff are used in Europe and many other countries. In this model, the energy price is fixed and is applied to all energy producers. Utilities are obliged by legislation to provide access and a fixed price for electricity that is normally based on a cost plus normal profit margin. FiT is specific to the type of energy and may depend on the size of the project. It has been proven to be the best mechanism to promote renewable energy. [33]

Energy prices were established according to the Renovar Program for renewable energy projects. The last round had the following bid prices per energy:

Type	Min Bid Price	Mean Bid Price
Wind	37,30	47,64
Solar	40,44	48,67
Biomass	92	107,07
Biogas	150	157,97
Hydraulic<50MW	89	97,28

Table 7 Energy bid prices at Renovar, Ministerio de Energía y Ambiente Argentina

According to the last table, a price of 47.65 u$/MWh for wind energy was used. For hydrogen technology, there is today no bid price, as no projects were presented. However, due to the nature of the fuel, this study estimates that a bid price of 157 u$/MWh can be used, which is the mean bid price for biogas.

5.1.2 Renewable energy credits and carbon credits

Revenue is also generated by renewable energy credit (REC) or carbon credit. Renewable energy credit is a proof of 1 MWh of renewable energy generation. It is used to prove and verify that the renewable energy obligation is met. This certificate has become a tradable commodity. Carbon credit is the other option. One carbon credit is equivalent to 1 ton of CO2. This credit is applied on the countries that have ratified the Kyoto Protocol, which defines caps on greenhouse gas emissions for a country. This country assigns then caps to utilities that produce greenhouse gases. This mechanism is an incentive for utilities to invest and promote clean energy generation and to invest in environment friendly technology. [33]

5.2 Sizing of the installation required for the case study

The installed wind farm can produce in a year 22.810 GWh of wind energy. From those, 534 GWh are curtailed (2% in total) and 22.276 GWh are effectively used.

Hydrogen production and storage capacity was defined by taking into account hydrogen production and storage costs, surplus energy available and the net present value of the project.

As mentioned in the previous chapter and the by simulation included in fig. 31, by increasing the hydrogen production capacity, more CO2 emissions were reduced as less energy is curtailed. However, capital expenditures increased to a point the net present peaked, because the marginal production capacity decreased.

Production and storage capacity must be analyzed together. A simulation is shown next, for the net present value of the project. It is clear at this point, that increasing production and storage capacity of hydrogen, will decrease CO2 emissions. But as mentioned, marginal gains decrease.

Table 8 shows the NPV for the scenarios simulated. The numbers of electrolysers and total storage capacity is variable and NPV are calculated. In green the best scenario is highlighted.

For this study, it is assumed for the calculation of the NPV:

- Project is funded 100% with equity
- Project pays no taxes

The project is evaluated by EBITDA, as it can be used to compare projects at different countries and regions. It is free of the effects of financial and accounting decisions. Renewable Energy policies vary between countries and regions. The project is only evaluated by its own operating income and leaves non operating incomes aside.

Tank/Elec	5	6	7
2500	2.592.409	2.646.703	2.503.902
2800	2.581.577	2.677.085	2.568.873
3200	2.529.900	2.657.182	2.585.910

Table 8 NPV results from simulation with varying storage capacity and number of electrolisers

With the optimal scenario, 4.387 GWh of hydrogen are effectively produced and stored, this is 97% of the potential hydrogen production. With an efficiency of the internal combustion engine of 42%, this amount of hydrogen produces 1.843 GWh of electrical energy.

5.3 Assessment of installation CAPEX and OPEX

5.3.1 Capital Expenditures

Capital costs are mainly turbine and balance of plant. The turbine cost is the most significant in a wind project with 70% of the total capital cost and include the turbine tower of 70 meters height, transport, installation, commissioning and control systems. Other capital costs included are: civil work (foundation and site access), grid connection, engineering and construction management.

Capital expenditures for a 4,5 MW wind park are included in the next table. This project has taken general costs of the Argentine market. Typical prices per kw installed range between 1.100 and 1.300 U$/kW.

To estimate total capital expenditures for wind energy generation, total installed cost of 1.200 u$/kW is used. Other costs are assigned based on their incidence in the cost structure.

CAPEX [U$]	5.400.000
Wind Turbine	70%
IMPSA 70-1500	2.520.000
NRG 64-1500	1.260.000
	3.780.000
Electrical Equipment	7%
	378.000
Civil Work	8%
Foundation	220.320
Site Access	211.680
	432.000
Grid	4%
	216.000
Financial	8%
	432.000
Engineering and Man.	3%
	162.000
U$/kW	1.200

Investment in hydrogen production were estimated with current ITBA projects and future technology improvement. Equipment needed:

- Self-pressurized alkaline electrolyser
- Hydrogen Tanks ITBA
- Converted Internal Combustion Engine

Tank cost: USD/kgH_2 (it includes valves and fittings)		
Storage Pressure (bar)	Conventional Steel Tank	Coiled Tank Al 7075-T651
150	200	160
480	1500	260
540	2000	280
875	-	500

Table 10 Tank cost of ITBA coiled tank Al 7075-T651 and conventional steel tank [34]

As seen from the table, storage costs are noticeably reduced. Total storage capacity of 2800 kg was estimated by the simulation. The variable cost used is 260U$/kgH2.

First assessment gives 500.000 U$ investment needed for the electrolyser development. [34] In this application study, as seen, a total of 6 will be used.

100.000 U$ costs is assumed for a 250 kW ICE ran on Hydrogen The retrofitting costs does not vary with the nominal power of the engine [34].

CAPEX [U$]	4.228.000
Electrolyser	3.000.000
Tank	728.000
ICE Hydrogen	100.000
Engineering	400.000

Table 11 Capex for Hydrogen production and application

5.3.2 Operating Expenditures

Wind Energy operating expenditures were estimated by benchmark of wind energy project at 0,02U$/KWh. The cost structure is given in the next table. [33]

OPEX [U$/year]	600.000
Operation and Maintenance	420.000
Land Rental	60.000
Management	84.000
Insurance and. Taxes	42.000
U$/kWh	0,020

With a total yearly hydrogen production of 4.387 GWh a total value of 0,024u$/kWh was estimated. Operating expenditures in hydrogen production are comparable to wind energy [34].

5.4 Results

The financial performance of an energy project is measured by:

- Net Present Value (NPV)
- Payback Period
- Internal Rate of Return (IRR)

The project has the following cash flow in a period of 20 years, where a residual value of 30% of the total equipment is estimated.

Cash Flow Total	-	1	....	20
Wind Energy CAPEX	- 5.400.000	-	-	1.620.000
Hydrogen CAPEX	- 4.228.000	-	-	1.268.400
Total CAPEX	- 9.628.000	-	-	-
Wind Energy Revenue	-	1.061.244	1.061.244	1.061.244
Hydrogen Revenue	-	693.229	693.229	693.229
Total Revenue	-	1.754.473	1.754.473	1.754.473
Wind Energy OPEX	-	- 456.207	- 456.207	- 456.207
Hydrogen OPEX	-	- 108.083	- 108.083	- 108.083
Total OPEX	-	- 564.291	- 564.291	- 564.291
EBITDA	- 9.628.000	1.190.182	1.190.182	4.078.582

5.4.1 Net Present Value

It is calculated by the net cash flow time series and the following equation:

$$NPV = \sum_{i}^{20} cash\ flow(i)/(1+r)^{i}$$

r – discount rate

i – year

If the project has NPV equal to zero, it means that the project just recovers investment made and financial costs and the discount rate is equal to the internal rate of return. The discount rate is estimated at 8%. This value is generally used in energy generation projects.

NPV (8%) = 2.677.085

5.4.2 Internal Rate of Return

The interest rate corresponding to zero NPV or the interest rate received.

Project	IRR
Total Project	8%
Wind Energy Project	9%
Wind Hydrogen Project	7%

5.4.3 Payback Period

It is a measure of the number of years it takes for a project to return the total investment. The sum of accumulated cash flow equals the investment made. For the total project in 11 years, only wind energy project 10 years and only hydrogen 12 years.

6. General Remarks

Rio Grande shows excellent wind conditions that are today not used. Instead gas turbines have to balance base and peak load at expensive economic and environmental costs. There are problems associated with wind energy. Mostly related to wind variations and unpredictability, that force grid operators to have flexible energy systems and power back up capacities.

Incorporating hydrogen storage to wind turbines, makes the power curve smoothly and more predictable. Power generation peaks are reduced to fill energy gaps, when wind drops. Although, this process has inefficiencies, it allows grid operators to incorporate more renewable energy generators and cut back up capacity. This in turn makes the grid more efficient as capacity providers are paid for their available power supply.

The NOA and South region of the country were promoted for their renewable energy potential. Both are ranked at top places for green energy generation. However, most of the countries power load is focused in the center. This forces transmission lines to be expanded at expensive costs.

Percentages of Hydrogen can be mixed blended safely with natural gas in the gas pipeline network, without much retrofitting needed. Hydrogen can make up to 5-20% of the mixture depending on gas composition and pipeline system. [36]

Fig. 38 shows the existing natural gas network in Argentina. Hydrogen can be used to transport clean energy in the country without need of further investment. As it can be seen, the natural gas networks connect NOA and South region of the country.

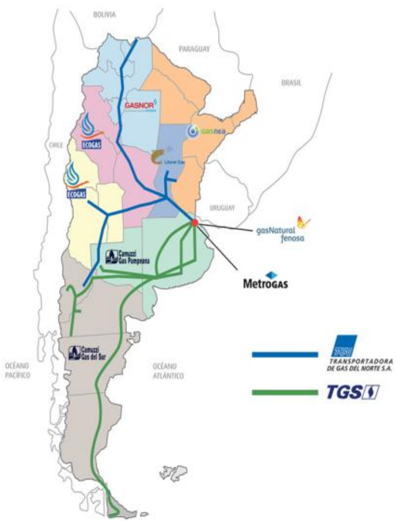


fig 38. Argentina natural gas network [35]

Other countries as Australia, Japan, Korea and Germany are working in advancement in Hydrogen technology and see Hydrogen not only for an environmental solution but also as a commercial alternative for the country.

Hydrogen technology is from a technically perspective a feasible project. From an economical perspective, with assumptions made in this application project, it seems possible to have a wind hydrogen energy system in the near future.

In Argentina there are now carbon credits market active. In Europe this market has functioned very well at 10 to 12 u$/TnCO2. Argentina has in the last years adopted policies to encourage investment in renewable energy technologies. The economic and financial feasibility of this project depends on these policies to make the energy transition possible.

Hydrogen production has very low efficiencies. The total process from wind to electricity, has an overall efficiency of 28%. However, if compared with a conventional power system the numbers are impressing. Primary energy is only used 30 % for heat and power. Total 26% is used in conversion systems of power plants refineries and cooking plants, 5% in own usage of the energy sector, 6% in non energetic uses and 36% is lost by the consumer. [37] Taking consumer lost in wind hydrogen system into account, overall efficiency is 18%.

Hopefully this project serves to gain insights in hydrogen technology and motivates further investigation. As in any other rising technology, studies and different approaches are needed. There is no correct pathway in this journey, only patience and optimism. Hydrogen has limitations, but its potential is unlimited.

7. Conclusions

The purpose of this work is to study the production of hydrogen with surplus energy from wind turbines at isolated places. For this work, Rio Grande was chosen for the application of the hydrogen storage technology. As Río Grande other isolated places exist in Argentina and in the world. Many have different renewable energy resources that are not fully exploited.

This studies approach was specific for Rio Grande energy situation. As an application study, some assumptions had to be made.

- This study did not have access to real wind conditions in an existing wind farm. For that reason, a wind energy project situated in Cabo Domingo was taken and wind estimation were done for this site.
- Rio Grande is not connected to the National Electric Grid. Information regarding power demand and supply were hard to get and estimations had to be done according to the Patagonia region.
- A scenario had to be set in which surplus energy could be gained. In this case, the priority was that the wind turbines with hydrogen storage were able to supply peak power demand. Base load was balanced with existing gas turbines. By doing this, wind energy curtailment of 2% was achieved. Also, gas turbines were kept at top efficiencies to reduce both energy costs and emissions.
- Hydrogen technology efficiencies and investment costs are based on ITBA experience in the field. Production equipment's are yet not commercial, and a great deal of work is still required.
- The economic analysis left financial and accounting decisions aside. In the purpose of this work, no taxes or incentives were included to keep this project unrelated to any region or country. Environmental and renewable energy policies are changing fast and some regions are more advanced than others.
- Hydrogen energy price was estimated based on Argentine bid prices in the Renovar Program for biogas.
- Rio Grande shows excellent wind conditions that are today not used. Incorporation of hydrogen storage to wind turbines would enhance the overall efficiency of a wind energy plant in 18%. Hydrogen technology is from a technically perspective a feasible project. Tt seems possible to have a profitable wind hydrogen energy system in the near future.

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Annexes

1. Electricity Production by Renewable Energies in Argentina, Ministerio de Energía y Ambiente, Argentina

RE Electricity Generation (GWh)	2011	2012	2013	2014	2015	2016
Biodiesel	32,5	170,2	2,2	1,6	0	1
Biomass	97	127	134	114	155	193
Wind Energy	16	384	447	613	593	547
Hydro < 50 MW	1255	1453	1274	1457	1624	1820
Solar Energy	2	8	15	16	15	14
Biogas	0	36	109	103	84	58
Total GWh	1.403	2.142	1.981	2.304	2.471	2.633
Argentine Electricity use	116.349	121.293	125.170	126.397	131.990	132.970
% RE	1,21	1,77	1,58	1,82	1,87	1,98

2. Primary Energy in Argentina in 2015, Ministerio de Energía y Ambiente, Argentina

	GWh	%
Natural Gas	487.706	52.42
Petroleum	311.307	32.27
Nuclear	25.615	2.01
Carbon	15.806	1.77
Hidraulic	41.026	4.22
Biomass	10.611	2.74

Vegetable Oil	9.344	3.34
Vegetable Alcohols	19.440	0.42
Wind	2.092	0.32
Solar	12	0
Other	4.242	0.48

3. Amount of electrolysers at 3500 kg capacity storage:

elect	WE curtailed	Ton CO2	NPV Total
1	- 2.251.342	30,05	- 296.143
2	- 1.778.959	56,61	698.957
3	- 1.369.424	79,63	1.501.287
4	- 1.024.919	99,00	2.101.091
5	- 745.578	114,31	2.476.650
6	- 534.048	125,33	2.616.271
7	- 382.278	132,84	2.562.461
8	- 274.787	137,67	2.360.683
9	- 197.797	141,00	2.057.530

10	- 144.408	142,00	1.683.061

4. Hydrogen Properties [34]

Effect of H2 compressibility on storage at 25°C	
Pressure (bar)	Density (kg/m3)
1	0,1
350	28,3
700	47,0
1050	60,5
1400	70,7

Hydrogen vs. conventional fuels			
1 bar, 25°C	Density (kg/m3)	IHV (MJ/kg)	Mass equivalent
Hydrogen	0.09	120	1.0
Natural Gas	0.72	45	2.7
Gasoline	750	44	2.7
Gasoil	810	42	2.9
Fueloil	970	41	2.9
Methanol	792	20	6.0