PEM ELECTROLYSERS FOR OPERATION WITH OFFGRID RENEWABLE INSTALLATIONS

Assessment of market potential

Deliverable 6.4

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D 6.4 Assessment of market potential

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Author(s)	Alfonso Bernad (FHa)
Participant(s)	Lorien Gracia (FHa)
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Executive Summary

This deliverable presents the market assessment for the ELY4OFF project, which looks for introduce the PEMWE into new markets with profitability and taking into consideration also the different synergies between different places.

Firstly, the deliverable presents an introduction of each target market, after what a detailed chapter for each of them is presented. Firstly, the role of hydrogen inside isolated areas is presented, showing that is still more profitable the use of traditional technologies in the mountain huts of Europe.

Then the hydrogen off-grid production is compared with the on-grid one. Via the suitable renewable energy source selection, a HRS with *in-situ* production of green hydrogen is profitable in countries with a future high introduction of the FCEV.

Another specific case presents how hydrogen is not only competitive but also a solution in the case of weak grids inside less developed countries, as African ones, providing a service when the scarce electricity grid fails.

Also the use of renewable hydrogen for industrial feedstock is another target market considered due to its future importance, although in this case the economic assessment was not done due to the similarity to the OFF-GRID HRS TO SUPPLY FCEVS case

Finally, a brief introduction of P2G technology prepare the path for future business cases which are going to be created inside the frame of the ELY4OFF project.

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LIST OF ABBREVIATIONS

BEV	Batteries Electric Vehicle
CAPEX	CAPital EXpenditures
CO_2	Carbon Dioxide
D	Deliverable
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FHa	Foundation for the Development of the Hydrogen Technologies in Aragon
GDP	Gross Domestic Product
GHG	Green House Gas
HRS	Hydrogen Refuelling Station
LHV	Lower Heating Value
NPV	Net Present Value
OPEX	OPerational EXpenditures
P2G	Power to Gas
PEMWE	Polymer Exchange Membrane Water Electrolyser
PV	Photovoltaic
UK	United Kingdom

1. INTRODUCTION

The strategic goal of the ELY4OFF project is the design and engineering of a robust, flexible, highly efficient and cost-competitive Polymer Exchange Membrane Water Electrolyser (PEMWE). The objective of this deliverable is to focus on the cost-competitive part, developing a specific market assessment with different target markets, while the design and engineering will be the basis for other tasks.

Currently, there are applications that are well known by their reliability and their profitability, however, a broader overview is presented here. This market assessment looks for a better understanding of where and how the hydrogen cycle could be competitive, even profitable.

Firstly, the desired markets have been identified, and after it, this deliverable aims to provide useful inputs to use in future business cases which will be realised in the frame of this project, as part of future deliverables as D6.8.

All this study is going to be structured following the Hydrogen Council Roadmap[1], as far as it represents the view that industry actors from the most important sectors have according to the evolution of these technologies and their view about the hydrogen transition, setting targets realistic for them. Figure 1 it presents where hydrogen is able to play an important role in the future, and gives a big overview about the different applications where hydrogen will be a solution.

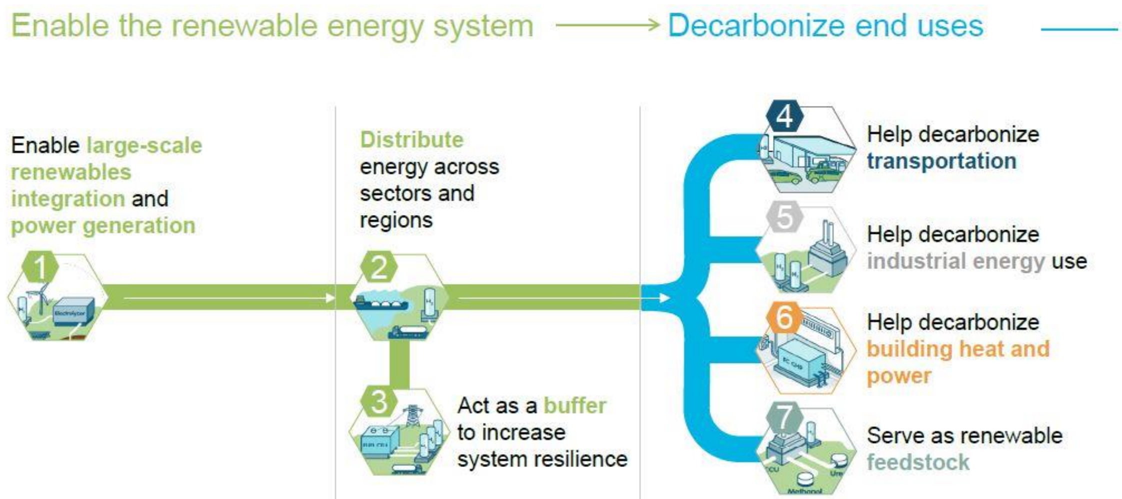

Figure 1: Hydrogen transition. Source: Hydrogen council[1]

The targets studied in this deliverable will cover just four out of seven possible fields: act as a buffer to increase system resilience, help to decarbonize transportation, help to decarbonize building heat and power and serve as renewable feedstock.

This does not mean that the hydrogen is not able to cover all of them. In this humble study, only some specific applications had been studied and analysed in order to see how the market could be according to each different situation.

The structure of each target market study follows the next structure:

- Brief definition of the target market.
- Main assumptions which has been done for each target market, where specific data is presented, and also a deeper explanation about the target market is presented, with different concerns that apply to each of them.
- Indicators: for each target market, specific indicators have been used in order to determine the countries to study. This indicators aims to present different scenarios to analyse, giving not only economic information but also social information that could affect the implementation of the FCH technologies.
- Economical study: A first economical assessment has been done, using specific data for each target market and trying to fit it in the most realistic way. The study has been set for a period of 20 years. More detailed information is available in the ANNEX: METHODOLOGY

What it is pretended with this preliminary study is to see under which conditions is possible to consider an off-grid hydrogen cycle, instead of the current technologies which are used to solve this problems nowadays.

The first target market, ENERGY SYSTEM FOR ISOLATED AREAS, will compare isolated regions, which today are feed by diesel gensets with a hydrogen off-grid cycle feed by renewable electricity provide by photovoltaic (PV) panels. This solution can primary avoids transport and diesel costs at the same time than reducing the Green House Gasses (GHG) emissions.

The second target market, considered in this study OFF-GRID HRS TO SUPPLY FCEVS, is focused on the mobility sector. Hydrogen is a well-known and technologically feasible solution to substitute fossil fuels as diesel working together in synergies with Batteries Electric Vehicles (BEV).The composition of a transport sector based on both technologies will create a key tool to reduce the greenhouse gasses and accomplish the Paris Agreement targets [2].

On-grid in-situ production has been compared with off-grid Hydrogen Refuelling Stations (HRS) feed with renewable resources. Thus, the hydrogen that will be charged in the Fuel Cell Electric Vehicle (FCEV) will be completely renewable, avoiding the emissions that a connected installation has, as a function of the electricity mix of each country.

Thirdly, inside the WEAK GRIDS AND BACKUP GENERATORS section, a broader scope has been looked for. Less developed countries also needs new technologies and hydrogen is able to play a new role there, acting as a backup generator in areas with weak grids, meanwhile can provide also off-grid electricity in isolated areas, as the first target market will explain. Moreover, according with the Paris Agreement [2], in its article 10.6, help should be provide from the most developed countries to the ones that are in development progress, in order to transfer technology and knowledge across the world.

Based on the reasons explained before, a comparison between diesel gensets in Africa and a renewable hydrogen cycle has been done, in order to face the problems caused by electricity outages, which are affecting not only the rural zones, but also the productivity and the economy of the continent [3].

Finally the hydrogen production for industrial feedstock has been also considered inside the European Union (EU) in the section GREEN HYDROGEN FOR NICHE INDUSTRIAL APPLICATIONS. Industry needs feedstock to operate, and hydrogen is one of them. Among its uses, hydrogen achieves an important international demand which is estimated nowadays at 55 millions of tons totally per year[1].

Power to Gas (P2G) is a more complex study which has to take into account not only the economic framework but also the legal aspects of each country. Based on these two main frames, a specific business case will be realised inside the frame of this project, being this deliverable just a brief introduction of the technology and the techniques and their efficiency. The business case will presents legal and technical information at the same time that covers in a more detailed way the technology needed in each case.

2. ENERGY SYSTEM FOR ISOLATED AREAS

Europe is formed mainly of developed countries with strong electricity grids. However; the existence of regions or places without access to electricity, or with important electricity concerns is a fact. Due to it, the first target market, energy systems for isolated areas, will be set just in the EU isolated areas.

2.1 Main assumptions

Two different cases are explained and considered in this study: mountain huts and isolated islands. The first one are isolated buildings electrically talking, being located far away from any other population core. The aim of this building is to serve as coverage for the mountaineers, in zones away for the population cores, being the main reason that forces the introduction of *in-situ* electricity production to cover the energy demand that each mountain hut faces as far as there is no electricity grid that allows them to obtain the electricity.

This *in-situ* production is mainly based on diesel gensets, creating added costs as the transportation of the fuel to the hut, mainly by helicopter, and emitting CO_2 to the atmosphere (directly by the combustion of the diesel, indirectly by its transport).

Nevertheless, nowadays there are also huts with renewable resources. These huts have hybrid systems between diesel gensets and renewable production. Meanwhile it is an easy tailored-made solution; hydrogen can play a role thus, to avoid the use of the diesel gensets, using a complete hydrogen cycle.

Isolated island face similar concerns. According to the geography, these islands are separated from the core of the nation they belong. This situation has two possible solutions: *in-situ* energy production via renewable or non-renewable resources; undersea wires, with high investment and maintenance costs and limited capacity concerns.

On the one hand, using the renewable *in-situ* production could carry curtailments by a local net injection into the local electricity grid bigger than the lines capacity. Nevertheless, the resources are near the demand limiting the losses due to transport and distribution, and the use of fossil fuels can be limited in this cases.

On the other hand, the undersea cables can be a solution, while the demand does not exceed the maximum lines capacity, which is able to cause an outage [4]. This outage will end in a huge amount of population affected by lack of service, situation that can be faced with an *in-situ* production.

2.2 Indicators

This study had set its focus only on mountain huts, being the electricity concerns more common in mountain huts than in isolated islands in Europe. Selected countries are France, Scotland (United Kingdom) and Slovenia, being the first and the seconds countries where important mountain systems are located and the third one a special case for a region with hiking routes.

Among them, what it has been compared is the energy consumption by hut, the diesel price in each country and the green energy production targets by country.

Table 1 presents the data about the energy consumption and the diesel price in each country. Both data will be used in the economic viability study.

Table 1. Target market indicators.[1]

Country	Emissions Year (Tonns of CO_2)[1]	kWh year of electricity[1]	Diesel Price (€/l) [5]
France	7.9	1,956	1.4
Scotland	4	978	1.7
Slovenia	14.8	3,965	1.38

The values presented in Table 1 are values measured *in-situ* from some representative huts in each country. This information is not easy to obtain and it suffers from a huge variation. An estimation of the average value for the whole country is hard to obtain and even though, it does not represent the proper reality of the extreme diverse that presents the mountain huts.

This study had taken into account the huts with guards and their situation. Huts in Slovenia are widely used, while Scotland has less guarded huts, and also with a smaller infrastructure.

Note that, and as long as all the countries studied in this target market are members of the EU, all of them have the targets from the 2030 Horizon (40% cut in greenhouse gas emissions (from 1990 levels), 27% of EU energy from renewable, 27% improvement in energy efficiency) and in order to accomplish them, and even more exigent ones, the EU members should move towards a green energy production, where hydrogen plays an important role.

2.3 Economic viability

In the mountain huts assumed in this study, a diesel genset with batteries is going to be compared against a renewable hydrogen cycle. Both cases had been designed to face the same energy demand in each case study. A peak of power demand of 5 kW has been selected to size the equipment.

[1] Own estimation, the data provided is based on previous work from the Sustain Huts Project (LIFE15 CCA/ES/000058)

The batteries had been seized in the genset case with energy enough to cover 5 days of the total electricity demand assumed. The technology used for these batteries is lead-acid, being the most common case in the huts.

The solution explained before has been compared with a renewable hydrogen cycle. In order to obtain the renewable hydrogen, the electricity that feeds the electrolyser needs to be from renewable resources. Looking for it, the technology solution chosen for this particular situation are PV panels.

Moreover, the compression stage and the electrolyser had been forced to work just in the hours with renewable production. From the storage perspective, the vessel will be prepared to work at 200 bar of pressure.

From the electricity production point of view, a fuel cell is added to close the system. The power of the fuel cell has been selected big enough to work under the manufacturers best practices advises.

A particularity of this situation arrives from the diesel demand and its transport to the hut. As far as mountain huts are in remote regions without road, the transport is done by a helicopter. The helicopter is able to transport the diesel with other needs as food, medicines, spare parts, and a long list of etcetera that a hut will need for its normal service.

To estimate the cost of this transport it has been assumed that the helicopter will be in a zone as far away as a hundred kilometres away of the hut. With just one trip it has been supposed enough to carry the entire amount of diesel for the whole year to the mountain huts.

Table 2. Economic assessment final results for isolated areas.

Target Market	FRANCE GENSET	FRANCE HYDROGEN	UK GENSET	UK HYDROGEN	SLOVENIA GENSET	SLOVENIA HYDROGEN
€/kWh	2.39 €	2.69 €	4.61 €	7.07 €	1.76 €	2.63 €
Investments	0.37 €	1.65 €	0.55 €	4.80 €	0.31 €	1.77 €
Replacements	1.01 €	0.63 €	2.33 €	1.18 €	0.67 €	0.50 €
Maintenance	0.07 €	0.41 €	0.11 €	1.09 €	0.06 €	0.37 €
Operational Costs	0.94 €	0.00 €	1.62 €	0.00 €	0.72 €	0.00 €

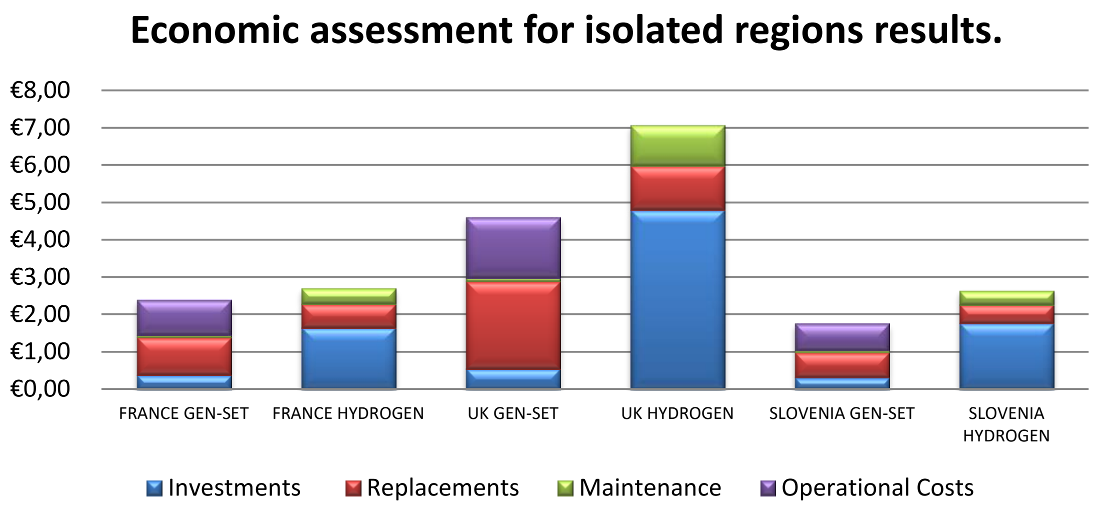

Figure 2. Results of the economical assessment of the isolated region target market.

Figure 2 presents the economic results of this target market. As a conclusion: the investments costs are the responsible factor that makes the hydrogen cycle less competitive than the diesel gensets.

In order to clarify how to improve this situation, a detailed view in the case of UK is presented below. As Figure 3 presents, the biggest responsible of the high investments costs are the PV panels, whose contribution is by 73 %.

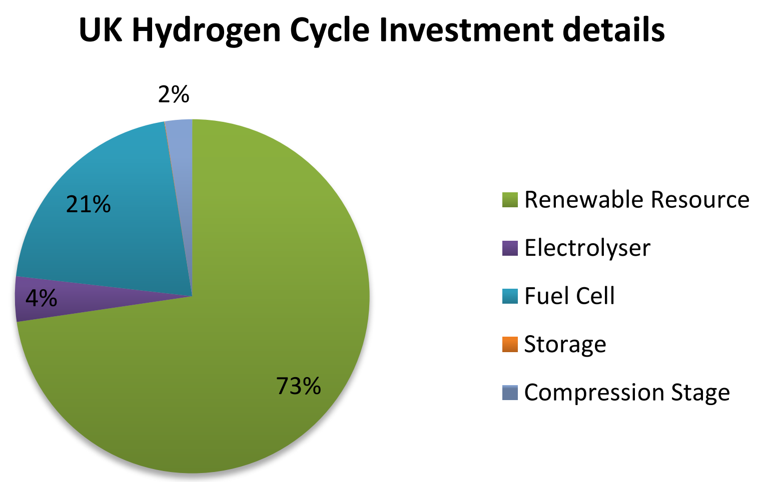

Figure 3. Detailed investment costs in UK isolated areas assessment.

A reduction in the price of the PV panels is expected in the near future, which can reduce the investment costs in this situation and make profitable the hydrogen cycle. However; the cost reduction of the PV panels will be also a potential risk as far as the hydrogen cycle could be replaced by PV panels and batteries.

The price of the fuel cell should also be noticed. The price of the fuel cell is higher than the electrolysers' one. This is based on the different uses. The fuel cell needs to be sized to cover the peak demand, taking into consideration the efficiency of these equipment. While the fuel cell needs to be oversized, the electrolyser is reduced, as far as the production hours, based on sunny hours, allows doing it.

3. OFF-GRID HRS TO SUPPLY FCEVS

Mobility is an exceptional market, as far as the targets for the EU looks for a limitation on the emissions in the transport. This is an objective which should be accomplishing working in the clean mobility direction, which should introduce not only pure electrical vehicles as BEV, but also FCEV.

3.1 Main assumptions

Companies as Toyota for FCEV or Nikola for trucks have been working with a clear main objective: drive the introduction of the fuel cells and hydrogen technologies in the market. As an example of the introduction on the market which is expected a clear target has been defined. An objective of a 3 % of the total annual sales of light duty vehicles worldwide covered by FCEV [1].

Extrapolating this situation to the EU, it is possible to develop a prediction of the amount of FCEV that will be running in the EU in 2030. Taking into account the inhabitants' growth of each country, and linking it with the amount of vehicles sold each year per country, an example of three countries is shown in Table 3. These countries will be France, Germany and Slovenia, as far as they differ enough among them, creating a sensibility analysis.

As a conclusion that could be extrapolated, while in France and in Germany, the amount of FCEV predicted allows to considered the creation of HRS grid infrastructure, in Slovenia, this HRS should be linked with captive fleets of buses or vans, to be profitable.

Table 3. Estimation of FCEV in Germany, Slovenia and France[2].

Country	France	Germany	Slovenia
Population 2018	67,290,016	83,429,059	2,067,603
Vehicles 2018	32,613,106	45,552,556	1,089,720
FCEV 2018	44	117	0
Population 2020	67,824,291	84,701,551	2,071,024
Vehicles 2020	32,872,050	46,247,341	1,091,523
FCEV 2020	1,790	4,797	12
Population 2030	70,559,973	91,361,128	2,088,215
Vehicles 2030	34,197,939	49,883,493	1,100,584

[2] Own elaboration data based on information available from [6] and EAFO web information.

FCEV 2030	23,837	65,290	158

Looking for the best comparison between the possible strategies in the hydrogen production, this study has compared an on-grid HRS with an off-grid one. The basis of this comparison is to look for a way to produce completely pure green hydrogen from renewable resources.

As far as the comparison needs to be fair, the same hydrogen demand has been used. This will help to use a similar structure. However, green hydrogen should be produced by renewable energy as solar or wind power, affecting the size of the electrolyser in each case, looking for maintaining the production according to the hours of production.

The HRS are composed by the basic components: a PEMWE MW scale, a compressor, storage tanks and the electricity source.

Looking for the computation of the off-grid operational costs, special focus needs to be done in two main equipment: electrolyser and compressor. Both have an equivalent electricity demand per normal cubic meter of hydrogen, and due to this value, the electricity need can be defined. Looking for the costs in the EU, Eurostat information [6] has been used as a database. This price is based on the industrial production, which fits with the scope of this task.

As estimation, the average kilometres that a vehicle will cover in a whole year has been selected as 15,000 km. Also, the estimation that a kilogram of hydrogen is able to cover a hundred of kilometres in a FCEV has been chosen.

3.2 Indicators

As it is explained before, the indicators in this specific target market are the average kilometres per vehicle per year, the amount of vehicles as a prevision which is explained in Table 3, and the trends that they presented.

As far as nowadays, the amount of vehicles is limited, it has been decided to not consider the HRS working at full load until 2030, when it is supposed that the FCEV share in the market will be big enough. Due to it, until that year, the amount of hydrogen produced in the HRSs will grow linearly each year. This assumption is based on the linear growth that has been predicted in the amount of vehicles estimation that has been presented before in Table 3.

Nevertheless, all HRS have been designed according to cover a demand of 500 vehicles per year in all countries. The need or not of this HRS will be based on the amount of planned vehicles. In Slovenia, where the amount of FCEV is planned to be small, the HRS is less useful than in Germany.

In order to consider the total amount of energy produced by renewable resources in each country, information about the energetic mix is used. Information available from [7] updated until 2016 has been used. Nuclear energy is studied separately from renewable resources; however, it has no direct CO_2 emissions, so it should be taking into account (France has a 70 % of nuclear energy). A potential target market according this social indicator will be the country with the lower percentage of CO_2 free electricity production.

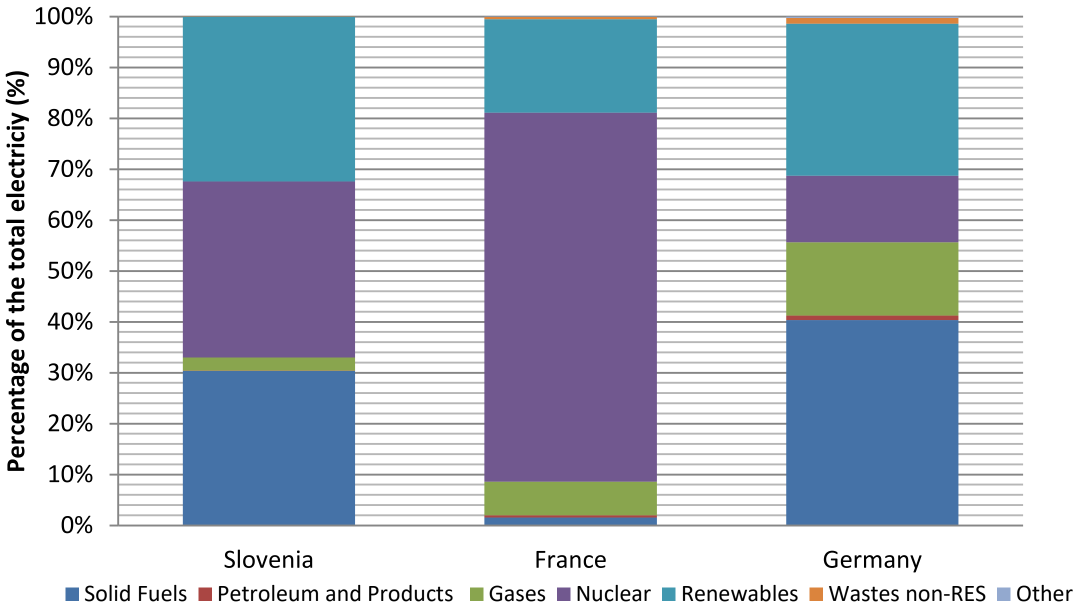

Figure 4. Contribution of each energy source to the electricity mix in 2016 in each country. Source: [7]

Summing up all the information, Table 4 presents which how potential market is each country.

Table 4. Final social assessment of each country in the off-grid HRS target assessment.

Country	Amount of FCEV	Inflation index	Energetic mix emissions
France	Medium	Low	Low
Germany	High	High	High
Slovenia	Low	High	Medium

3.3 Economic viability

As it has been explained before, the total demand on the HRS will be the same in both cases: off-grid and on-grid production. This total production has been estimated as 75 tons of hydrogen per year.

The overall costs that are included in the HRS are the compressor, the storage and the electrolyser. Moreover, an extra amount of 140,000 € is needed for the infrastructure costs and inner connections [8].

For the hydrogen production, the capital expenditures of the electrolyser, the compressor and the vessels are applied. The storage as been defined at 900 bar, as far as the standard for the pressure in the commercial vehicles is 750 bar, allowing thus to refill them.

The inner difference between both systems is born from the electricity source. The on-grid facilities are connected to the infrastructure of the country, and due to it, the price of this electricity depends on the market or on the regulated price. Data available from the EU has been used in order to establish fair prices. These prices, whose evolution is shown in the Figure 5, are obtained from the industrial scale, as far as the size and electricity demand for the electrolysers is big enough. Taxes are omitted in this study.

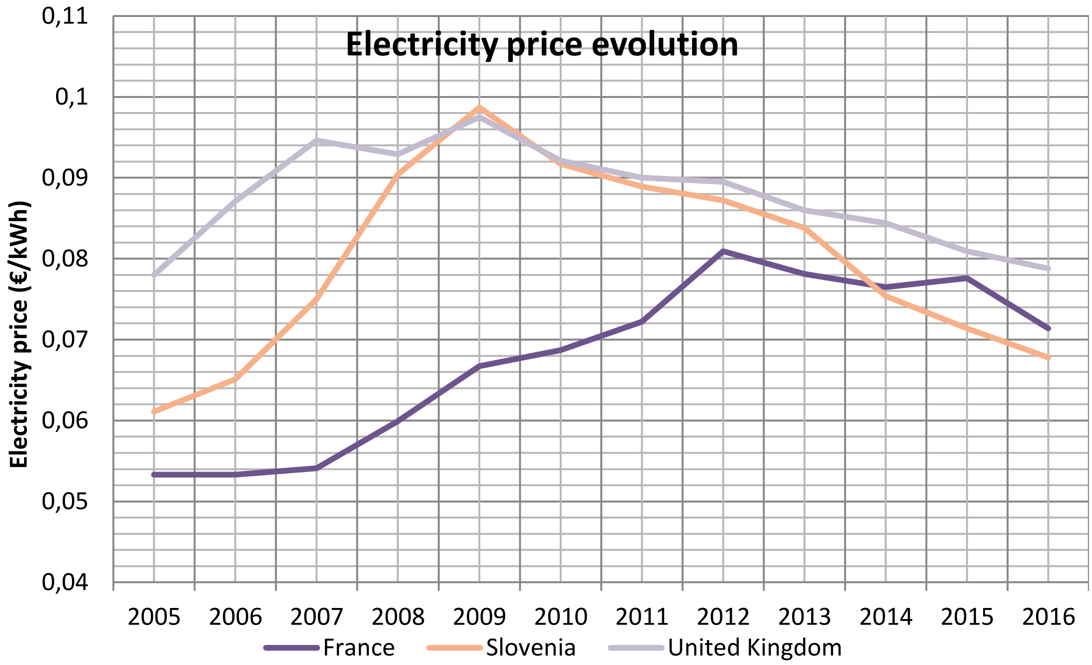

Figure 5. Electricity prices in the EU. Source: [6]

From the off-grid production, the electricity is produced from renewable resources. Being the electricity demand high, the electricity will be produced from wind power generation. The selection of wind power instead of PV panels in this market assessment has been based on the big amount of space and installed capacity that is needed from the PV panels, and the fact that a wind turbine is able to produce electricity more hours than the PV panels as average, allowing to size the electrolyser in a small scale than in the PV case, thus reducing the general investment costs.

Final results of the on-grid versus off-grid facilities that had been designed are shown below.

Table 5. Economic assessment final results for Off-grid HRS.

Target Market	FRANCE GRID	FRANCE WIND	GERMANY GRID	GERMANY WIND	SLOVENIA GRID	SLOVENIA WIND
€/kgH_2	10.13 €	9.70 €	11.38 €	9.13 €	10.55 €	9.30 €
Investments	1.75 €	4.48 €	1.73 €	4.08 €	1.73 €	4.19 €
Replacements	3.29 €	2.79 €	3.27 €	2.77 €	2.94 €	2.77 €
Maintenance	0.75 €	2.43 €	0.77 €	2.28 €	0.77 €	2.34 €
Operational Costs	4.33 €	0.00 €	5.61 €	0.00 €	5.10 €	0.00 €

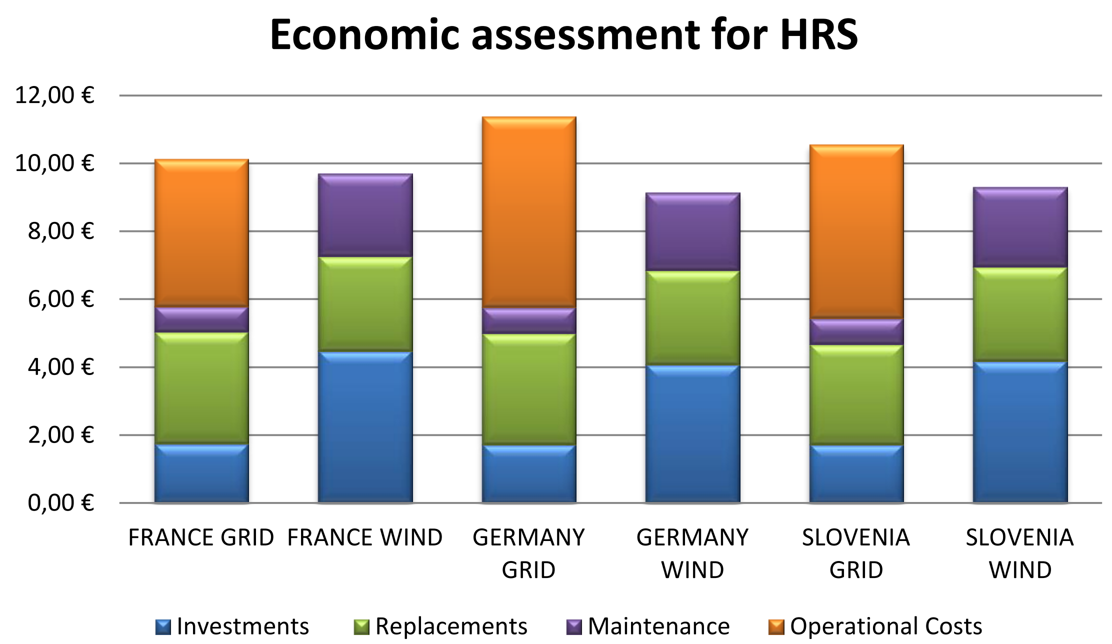

Figure 6. Final results for Off-grid HRS economic assessment.

Two comments needs to be introduced in this target market.

- The economic viability of the off-gird solar installation is far away for being profitable. Due to the relatively small amount of hours of sun, the introduction of the electrolyser just in that few hours increase its size. As the size increase, the needed capacity of the solar field does so. Due to it, the investment costs, and also the replacement ones increase in this situation.
- The economic viability of the wind power situation needs to be studied in more detail. The basic assumption of 5,000 hours of wind is set in all the cases, in order to facilitate the computation. A more detailed study will be done into a specific business case, sizing properly the wind power facilities with more detailed wind data.

4. WEAK GRIDS AND BACKUP GENERATORS

This target market is deeply focused in development countries, mainly in Africa. Inside our globalized world, African countries form a group which has a big perspective of growth [9]. Other countries as India and also countries from Asia could be also covered by this study; nevertheless, only three countries in Africa will be studied. These results should not be extrapolated directly to any other country, because each of them has a different idiosyncrasy to consider separately.

4.1 Main assumptions

In order to select which countries had been selected for this study, it has been necessary to look for three which could fit with a high, medium and low profile, allowing comparing three different situations and obtaining where it could be more valuable the introduction of a hydrogen cycle.

According to business environment, Africa is suffering a slowdown in their growth caused, among other things, by the electricity outages. These outages are related to problems in the generation and also problems related with the grid infrastructure which, as shown in Figure 7 is not strongly developed.

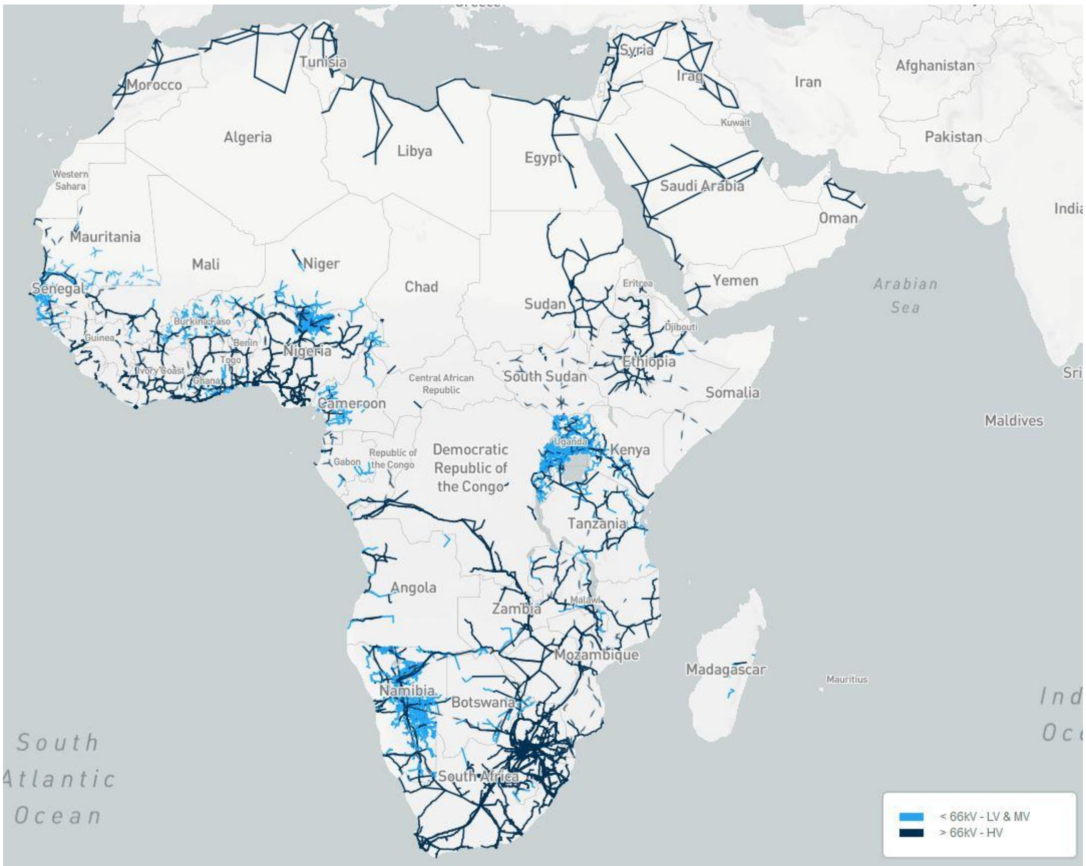

Figure 7. African electricity grid. Source: [10]

Fighting against these situations is done mainly by two different strategies: biomass or diesel gensets [3]. The use of this technologies causes extra costs, while do not help in the development of the electricity grid which should be, in a final stage, reliable and well developed connecting each population of the country with a mess grid.

Moreover, if a deeper focus is considered in sub-Saharan Africa, just 318,000 km of pavement road existed in 2014 (estimation of [3]). This infrastructure may create problems also in the distribution of the diesel from the oil stations till the final customer, creating an added value and also increasing the difficulties to provide electricity.

This target market aims to compare thus gensets generators with lead batteries versus hydrogen cycles with renewable energy (PV) in an isolated situation, as it could be a hospital or a little region. The consumption is based in proper estimation.

An estimated consumption of 3 kWh of energy has been defined. This is based on the typical basic demand of indispensable items in a little hospital, which is also bigger by far with the estimated electricity demand of 100 kWh per year in a rural zone in Africa[3].

Finally, the three countries selected for this study are Benin, Ivory Coast and Mali. Below this section, the different indicators are explained, thus how they are evaluated.

4.2 Indicators

One way to create a fair comparison among countries is based on using the Gross Domestic Product (GDP). GDP is, by definition, the monetary value of all the finished goods and services produced inside a country during a specific period of time.

In other words, it can be understood as a richness indicator, which allows the comparison among different countries. It can be also used to estimate the productivity of various countries. Due to it, this indicator has been selected to compare different countries along the African continent, giving a first impression of which will be the best target market.

Figure 8 presents the GDP evolution from 1960 till 2016 of the three countries that fall under the scope of this project. A fast conclusion that this figure shown is that Ivory Coast has a more developed economy, while Benin and Mali have a less developed one.

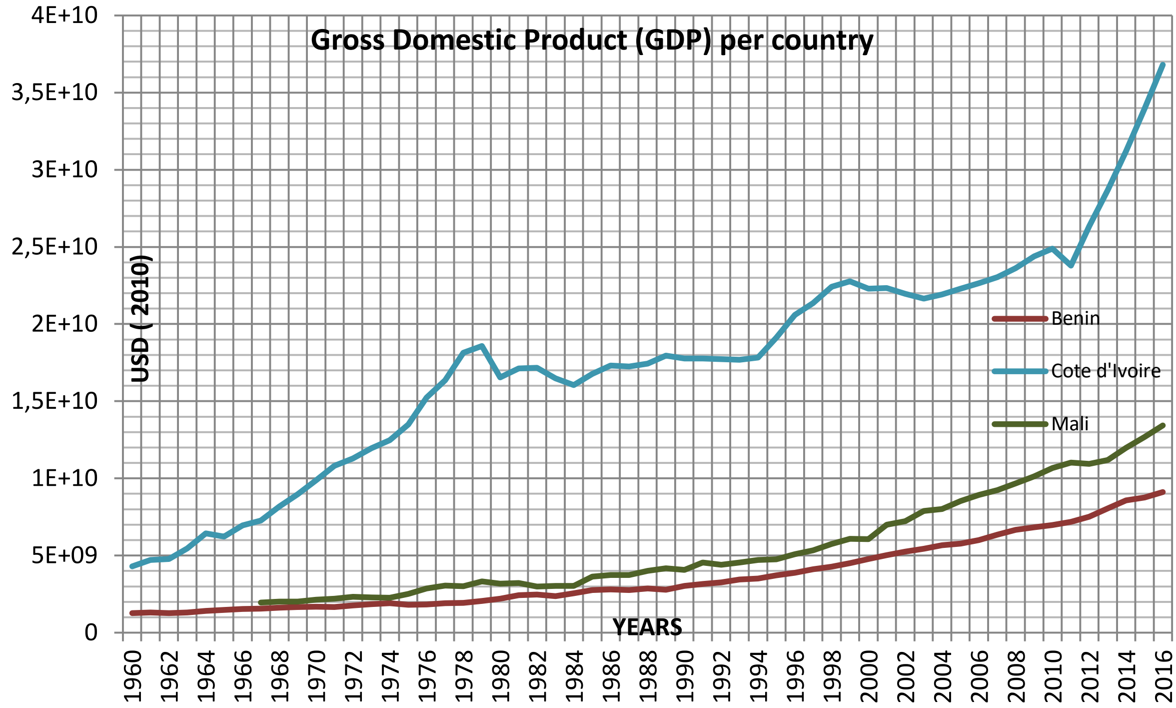

Figure 8. Historical Gross Domestic Product evolution per country in Africa. Source: [5]

Once the GDP has been evaluated, and as it has been explained before, the productivity is affected also by the outages and grid constraints. However, even more important that the grid constraints is the percentage of population with access to electricity in each country.

As Figure 7 has presented, the african electricity grid presents the two sides of the situation: zones deeply developed as in South Afican, and countries with a scarce electricity grid as Mauritania.

Observing the three countries defined in this study, just Ivory Coast has a deeper developed grid, with a percentage bigger than 60 % nowadays. Benin and Mali have a less developed ones, with less than a 40 %. This situation is even more extreme in rural zones, where the access to the electricity, according with information from Word Bank Data [5], does not exceed the 40 % for example in Ivory Island. Asumming that, the three countries selected can be studied also as isolated regions.

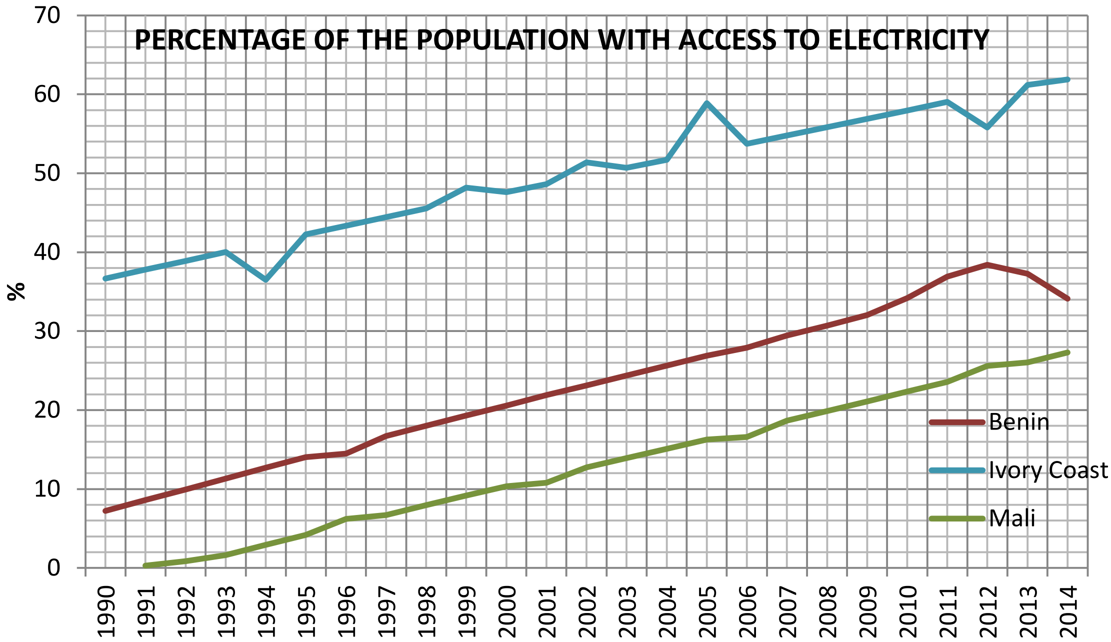

Figure 9: Percentage of population with access to the electricity Grid. Source: [5]

The last indicator of Africa, to compare the different countries has been the outages information that is available from Enterprise Survey [11]. This information, which is deeply linked with the productivity of the countries [3], shows that in the different countries selected, the amount of hours without electricity access differ hugely among the countries.

Table 6. Outages in Africa information. Source: [11]

Country	Year	Percent of firms experiencing electrical outages	Monthly number of electrical outages.	Average duration in hours of electrical outages.	Annual hours of outage
Benin	2016	95.6	28.0	3.7	1,243.2
Ivory Coast	2016	78.8	3.5	5.5	231
Cameroon	2016	92.5	7.6	8.7	793.44
Guinea	2016	84.2	4.5	3.2	172.8
Liberia	2017	44.3	4.5	8.3	448.2
Lesotho	2016	71.8	2.2	6.6	174.24
Mali	2016	86.6	4.2	5.1	257.04
Niger	2017	78.0	22.0	5.2	1,372.8
Sierra Leone	2017	71.8	9.1	13.5	1,474.2
Swaziland	2016	77.3	3.7	3.7	164.28
Togo	2016	93.8	5.5	2.1	138.6
Zimbabwe	2016	76.5	4.5	5.2	280.8

According to this information obtained, a brief comparison among the countries has been defined, thus, it gives some priority market lines to consider as shown in Table 7.

COUNTRY	GDP	% Population with grid access	Outages hours
Benin	Low	Medium	High
Ivory Coast	High	High	Low
Mali	Medium	Medium-Low	Low

Table 7. Comparison among countries in Africa

4.3 Economic viability

The same diesel genset that is able to provide power enough to supply energy as a backup system has been used in all the situations. The equipment's size has been selected according to manufacturers, which recommend that gensets work at a 75 % of their full load.

The hydrogen cycle has been seized particularly in each situation, assuming that the fuel cell has an estimated efficiency of 50 % and that the PEMWE has a 60 %. The storage is set to work to 200 bar of pressure, as far as the amount of hydrogen is not going to be high, reducing the costs.

The electricity in this field will be provided by PV panels for the backup. This is suitable due to the fact that the total amount of hours of sun is bigger than the total amount of outage hours, being possible to produce hydrogen slower than it is going to be consumed.

In order to estimate the costs of the diesel in each situation, the transport will be compute in a different way. The diesel in this region is assumed to be done by truck. 100 kilometres of distance has been selected as the average distance per country, and the truck diesel demand has been estimated as 30 litres per each 100 kilometres in a 30 tons truck [12]. The diesel cost is estimated with data from [5].

Final results are presented in Table 8 and in Figure 10.

Table 8. Economic assessment final results for weak grids.

TM	BENIN GENSET	BENIN HYDROGEN	IVORY COAST GENSET	IVORY COAST HYDROGEN	MALI GENSET	MALI HYDROGEN
€/kWh	1.11 €	1.06 €	4.32 €	2.12 €	4.02 €	2.11 €
Investments	0.05 €	0.77 €	0.25 €	1.58 €	0.22 €	1.61 €
Replacements	0.12 €	0.04 €	0.0 €	0.05 €	0.0 €	0.10 €
Maintenance	0.01 €	0.25 €	0.04 €	0.49 €	0.04 €	0.41 €
Operational Costs	0.94 €	0.0 €	4.03 €	0.0 €	3.76 €	0.0 €

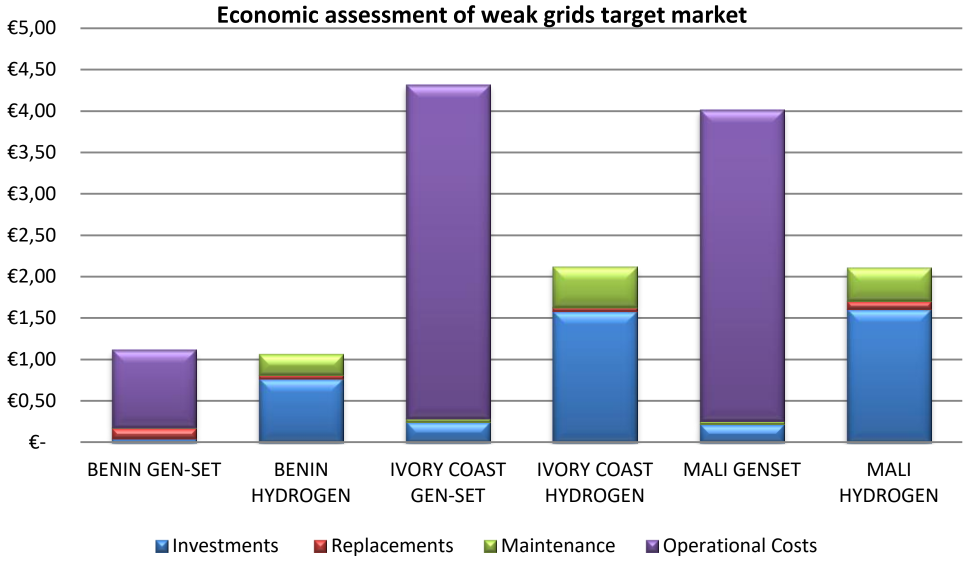

Figure 10. Results of the market assessment in the weak grids target market.

This target market is promising. The operational costs related with the diesel transport and its demand is the biggest part of the costs, being in the Ivory Coast example around the 90 %. Avoiding them with the in-situ generation of hydrogen allows decreasing the general costs. As conclusion, the investment costs growth but, the fuel cell and the electrolyser reduce the replacements as far as the use of the equipment is minimized, as happens with the maintenance.

The total contribution in each situation of the target market and how each parameter contributes with the final costs are presented in Figure 11.

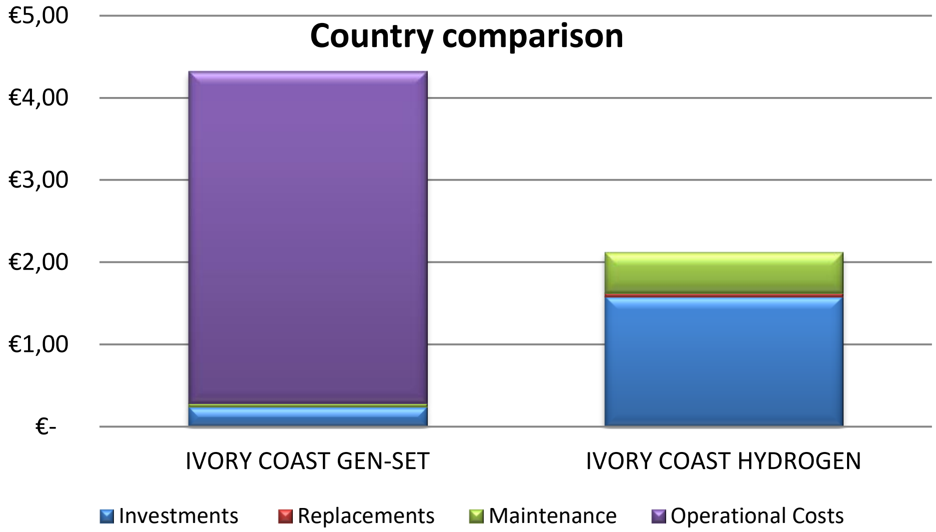

Figure 11. Detailed overview of the contribution of each individual cost in the final price in the weak grids target market.

5. GREEN HYDROGEN FOR NICHE INDUSTRIAL APPLICATIONS

As it has been explained before in the I, the renewable hydrogen for industrial feedstock will be another target market to consider due to its future importance. [1] Notice that in this chapter there is no economic assessment due to the similarity to the OFF-GRID HRS TO SUPPLY FCEVS case.

5.1 Main assumptions

Looking for a deep and complete demonstration and understanding about what hydrogen economy should face in the future, it is important to consider not only the new targets. Hydrogen has been widely used in the industry. Green hydrogen has potential traditional markets, as far as nowadays, the greatest amount of hydrogen for industrial uses comes from the Steam Methane Reforming(around a 48 %), followed by its production as a fraction of the petrol refined (30 %)[13].

In a society that trends to a strong decarbonisation in all the sectors, industry needs fast and effective actions in order to achieve its target. Due to it, avoiding the GHG and CO_2 emissions, when possible, should be understood as an important target (Horizon 2030).

Hydrogen produced by electrolysis could cover all the current industrial uses of the hydrogen[1]. Between all the markets, one of the most important ones, according to their production and also their importance worldwide is ammonia manufacturing[14,15]. Other markets are defined in Table 9.

Table 9: Industrial applications of hydrogen and yearly volume: Source: [15]

INDUSTRY	MARKET SHARE	KEY APPLICATIONS	SUPPLY SYSTEM	H_2 DEMAND
General industry	1 %	Semiconductor and cooling of electrical generators	Small on-site production	>0.7 Mtons
Metal Working	6 %	Iron reduction Forming gas	Tube trailers	0.41 Mtons
Refining	30 %	Hydrocracking Hydrothreating	Pipeline Large On-Site	2.1 Mtons
Chemical	63 %	Ammonia Methanol Resins	Pipeline Large On-Site	4.3 Mtons

As Table 9 has shown, there is a big amount of hydrogen that could be produced from renewable resources avoiding emissions to the atmosphere and saving other raw materials.

To obtain a fair comparison, the same amount of hydrogen will be needed, reason why the economic assessment of the chapter OFF-GRID HRS TO SUPPLY FCEVS is valid also in this chapter.

5.2 Indicators

The EU has been set as the frontier of this target market. Moreover, the same countries that have been selected for the target market 2 have been selected to be studied in this target market.

As Figure 12 presents, the electricity demand is widely higher in France and Germany. This is related not only with the population, but also with the intensity of each activity. The economy is more developed in Germany and industry is one of the main activities in the energy consumption of the country. The information presented gives a scale indicator about the amount of industry in each country, being also important the transport final energy consumption which is also linked with this industrial activity.

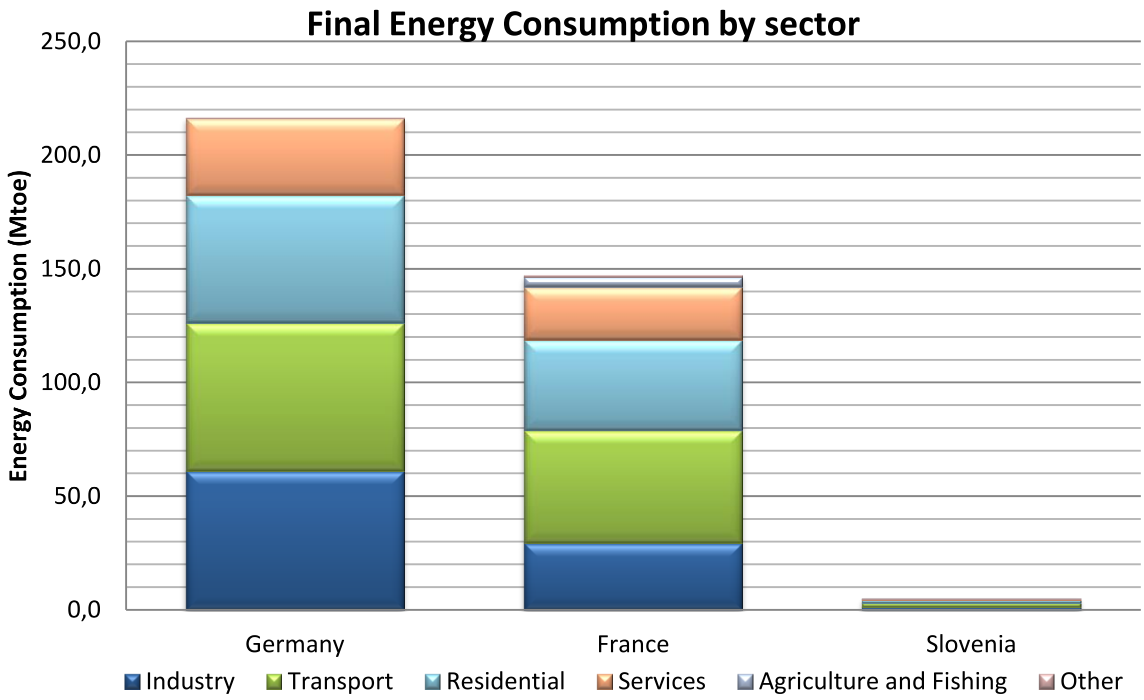

Figure 12. Final energy consumption by sector (Mtoe) per country. Source: [7]

According to the emissions, this indicator follows the same structure than the previous one, as Figure 13 presents, the emissions are higher in Germany than in France and Slovenia. This is caused by the energy mix and also by the size of the industry in the country. Due to it, the final indicators of these countries are summed up as Table 10 presents.

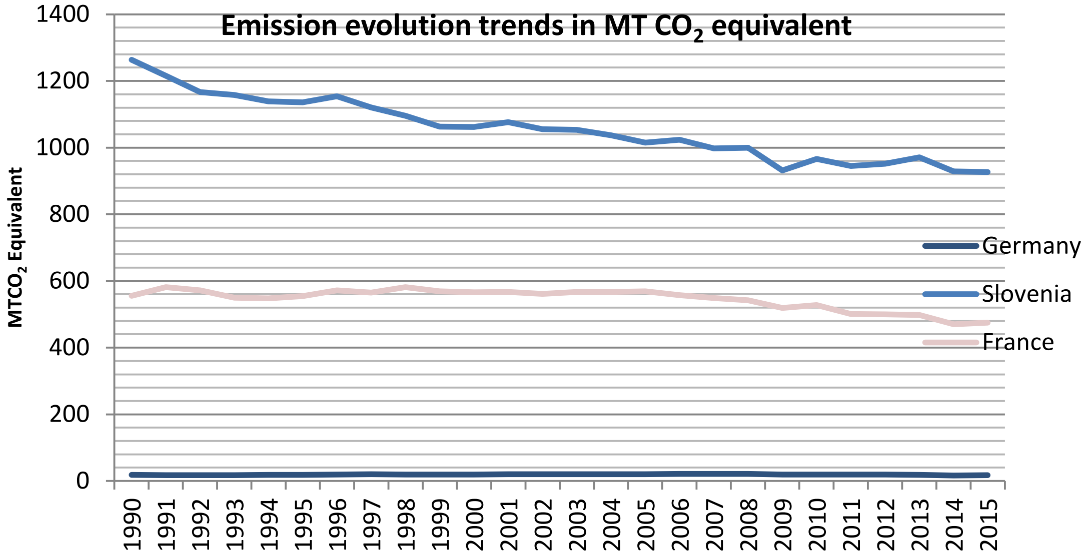

Figure 13. Emissions evolution in MT CO_2 equivalent per country. Source: [7]

Table 10. Social indicators for green hydrogen in each country.

COUNTRY	Industry scale	Emissions
France	High	Medium
Germany	High	High
Slovenia	Low	Low

6. OTHER FIELDS: P2G

Due to the limit scope of this study, there are other possible target markets that are well known but are not considered. Among them, one is the P2G field [13]. P2G will be studied in the future deliverable D6.8 and a whole business case will be developed about it.

This solution has been briefly explained during the whole document; however the basis is the next one: using electrolysis to split water molecules into oxygen and hydrogen, which can be use or storage directly, injected into a pipeline to transport it, or can be used to produce synthetic natural gas to blend in the current natural gas grids.

Being the common step the production of hydrogen via electrolysis, there are different ways to use it, creating products as fuels or gasses which are needed in different fields. Figure 14 shows which the different options are and how efficient is each process. The data were obtained from [13], and presents which how much from a 100 % of electricity is finally available.

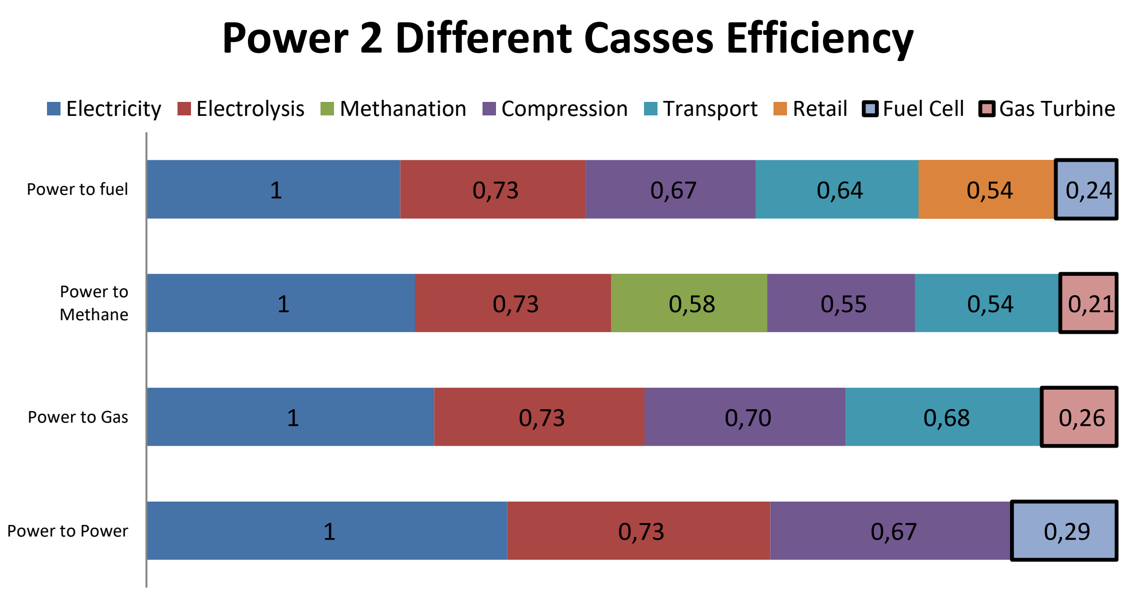

Figure 14. Efficiencies of P2X. Source: [13]

As far as the efficiencies presented can be seen as low, it is important to consider when P2G can be a reality and has a chance to be effective. Considering, as an example, the grid curtailments explained among this document, P2G technology can be used to storage the surplus of renewable energy in hydrogen (or other synthetic gas) for a long period, and be available when the demand exceeds the production installed capacity, using only the surplus electricity when it can be produced at low cost.

This storage capacity is important to reduce the use of carbon or gas centrals, by using the surplus produced as an example in summer with solar PV electricity, in winter.

Another important field of P2G is the synthetic gas manufacturing. Nowadays the injection of hydrogen inside the current natural gas grids may be limited by technical [16] and legal concerns in the EU. As a maximum blend level of H2 into the gas grid, the actual value of 0.1%vol for the UK (even if it is expected to evolve) as the most sever legislation (then Sweden also with 0.5%vol). It depends also of the use of H2.

To summarise, the scope inside the EU varies widely being allowed to inject from 5 % (mol) in Spain in a mixed injection of synthetic natural gas [17] (it is not allowed to blend directly just hydrogen) till 10 % in Germany.

As it has been explained, this target sector will be study in detail in future work of this project.

7. CONCLUSION

As it has been presented, there are some markets that can be profitable as backup generation in less developed countries, meanwhile the stronger markets as mobility, are still an interesting option for the off-grid hydrogen production.

ENERGY SYSTEM FOR ISOLATED AREAS have presented that the gensets with batteries are still the most reasonable solution, based on the high investment costs, not only of the FCH technologies but also related with the high costs of the renewable resources.

The target market OFF-GRID HRS TO SUPPLY FCEVS has presented that off-grid production falls under an important issue. Due to the intermittency of the energy source, the electrolyser needs to be oversized to obtain a complete off-grid production, and also the renewable energy production source, increasing the investment cost, and causing a less profitable situation. Nevertheless, with highly intensive energy sources as wind power generation, the off-grid systems are economically feasible.

WEAK GRIDS AND BACKUP GENERATORS had been presented as an economic solution with hydrogen technologies. Moreover is in these countries, where the higher part of the cost are related with the operational costs, presents a niche market for the off-grid hydrogen production and use, avoiding problems not only for the productivity of the country but also improving the quality of life of their inhabitants.

GREEN HYDROGEN FOR NICHE INDUSTRIAL APPLICATIONS is also important, but it has to face the same concerns of the OFF-GRID HRS TO SUPPLY FCEVS target market. In this specific topic, the most developed countries are the ones that should start to move towards the hydrogen transition.

8. REFERENCES AND BIBLIOGRAPHY

1. Hydrogen Council, *Hydrogen scaling up A sustainable pathway for the global energy transition, Hydrogen Council*, (2017).
2. Convención Marco sobre el Cambio Climático, *Acuerdo de París sobre el Cambio Climático, UNCCC*, Paris, (2015).
3. IEA, *Africa Energy Outlook A focus on energy prospects in Sub-Saharan Africa, IEA*, (2014).
4. Tracteberl Engie and Hinicio, *Study on early business cases for H2 in energy storage and more broadly power to H2 applications, FCH JU*, Belgium, (2017).
5. The World Bank, Database, *Wold Bank* (2018).
6. Euorstat, Database - Eurostat, *EuroStat* (2018).
7. European Comission, Database European Comission Energy, *Energy* (2018).
8. Thomas D. (Hydrogenics) et al., *Power To Gas Radmap for Flanders*, Brussels, (2016).
9. World Energy Council, *Regional Perspective for Sub-Saharan Africa*, (n.d.).
10. Africa Electricity Grids Explorer, Africa Electricity Grids Explorer, (2018).
11. Enterprise Surveys - World Bank Group, *Enterpise Surv.* (2018).
12. Nylund N.O., Erkkilä K, Heavy-Duty Truck Emissions and Fuel Consumption Simulating Real- World Driving in Laboratory Conditions, (2005).
13. IEA, *Technology Roadmap Hydrogen and Fuel Cells, IEA*, France, (2015).
14. Fraile D., Lanoix J-C., Maio P., Rangel A., Torres A., *D11 Bibliographic review of market outlooks for hydrogen in Europe, FCH JU*, (2015).
15. Fraile D., Lanoix J-C., Maio P., Rangel A., Torres A., *D12 Overview of the market segmentation, FCH JU*, (2015).
16. Altfeld K., Pinchbeck D., Admissible Hydrogen Concentrations in Natural Gas Systems, *Gas Eur.* (2013) 16.
17. Industry, Turism and Comerce Ministry of Spain, *Detailed Protocol 01 "Measurement, Quality and Odorization of Gas,"* (2011).
18. Central Intelligence Agency, The World Factbook, (2018).

ANNEX: METHODOLOGY.

This study has followed a cash flow methodology. Each of the target markets has different inputs which have been used to size the different equipment that compose the solution study and thus, the estimation of the overall costs has been done.

The output in each target market is the price of energy unit or kilogram of hydrogen based on the total production and the total Net Present Value (NPV) of the project.

For each target market, the inputs are showed in the Table 11. As it is presented, the variation per country does not only depend on the situation, because also economic factors are used, as the inflation rate of the country (selected the inflation rate for 2017 with CIA World Fact book as a source[18])

Table 11. Inputs for each target market analysed.

<table>
<tr><td colspan="7">TARGET MARKET 1. ISOLATED REGIONS</td></tr>
<tr><td>COUNTRY</td><td colspan="2">Annual Electricity Demand (kWh)[3]</td><td colspan="3">Annual hours of sun (h)</td><td>Inflation[18]</td></tr>
<tr><td>France</td><td colspan="2">1,956</td><td colspan="3">2,200</td><td>1.2 %</td></tr>
<tr><td>Slovenia</td><td colspan="2">3,065</td><td colspan="3">2,700</td><td>1.6 %</td></tr>
<tr><td>Scotland</td><td colspan="2">978</td><td colspan="3">1,400</td><td>2.6 %</td></tr>
<tr><td colspan="7">TARGET MARKET 2 OFF GRID HRS</td></tr>
<tr><td>COUNTRY</td><td>Total production of Hydrogen (kg)[4]</td><td>Annual hours of sun</td><td>k</td><td>c</td><td>Annual hours of wind[5] (h)</td><td>Inflation[18]</td></tr>
<tr><td>France</td><td>75,000</td><td>2,200</td><td>2.5</td><td>8</td><td>5,000</td><td>1.2 %</td></tr>
<tr><td>Germany</td><td>75,000</td><td>1,400</td><td>2.15</td><td>8</td><td>5,000</td><td>1.6 %</td></tr>
<tr><td>Slovenia</td><td>75,000</td><td></td><td></td><td></td><td>5,000</td><td>1.6 %</td></tr>
<tr><td colspan="7">TARGET MATKET 3. WEAK GRIDS</td></tr>
<tr><td>COUNTRY</td><td>Outage hours (h)</td><td>Electricity demand as backup (kWh)</td><td colspan="2">Annual electricity demand (kWh)[6]</td><td>Hours of sun (h)</td><td>Inflation[18]</td></tr>
<tr><td>Benin</td><td>1,243</td><td>3</td><td colspan="2">3,729</td><td>1,800</td><td>2.0 %</td></tr>
<tr><td>Ivory Coast</td><td>231</td><td>3</td><td colspan="2">693</td><td>1,800</td><td>1.0 %</td></tr>
<tr><td>Mali</td><td>257</td><td>3</td><td colspan="2">771</td><td>3,000</td><td>0.2 %</td></tr>
</table>

Once all the inputs have been introduced, the next step has been the sizing of all the elements that are going to form the energy system.

According to each target market, the different components have been sized, and selected to achieve the minimum energy demand that is required.

[3] Data obtained from the Sustain Huts project. LIFE15 CCA/ES/000058
[4] Own estimation explained in OFF-GRID HRS TO SUPPLY FCEVS.
[5] First assumption based on a good perspective of hours.
[6] Data obtained from a demand of 3 kWh and the number of outages [11]

For the investment costs, and also for other values as the lifetime of each technology reference [8] has been used. The selected values are presented in Table 12:

Table 12. Economic data used in the study.

COSTS	YEARS		
Genset Small size[7]	2015	2030	2050
Lifetime (hours)	10,000	10,000	10,000
CAPEX (€/kW)	875	875	875
OPEX (% CAPEX)	1	1	1
Diesel consumption (l/kWh)	0.3922	0.3922	0.3922
Genset Medium size[7]	2015	2030	2050
Lifetime (hours)	10,000	10,000	10,000
CAPEX (€/kW)	460	460	460
OPEX (% CAPEX)	1	1	1
Diesel consumption (l/kWh)	0.2889	0.2889	0.2889
Genset Big size[7]	2015	2030	2050
Lifetime (hours)	10,000	10,000	10,000
CAPEX (€/kW)	200	200	200
OPEX (% CAPEX)	1	1	1
Diesel consumption (l/kWh)	0.275	0.275	0.275
Battery	2015	2030	2050
Lifetime (hours)	87,600	87,600	87,600
CAPEX (€/kWh)	600	500	300
OPEX (% CAPEX)	1	1	1
ELY < 1MW	2015	2030	2050
Lifetime (hours)	40,000	50,000	60,000
CAPEX (€/kW)	1,500	1,000	550
OPEX (% CAPEX)	4	4.8	7.64
Efficiency (kWh/Nm^3H_2)	5.2	5.1	5
ELY > 1MW	2015	2030	2050
Lifetime (hours)	40,000	50,000	60,000
CAPEX (€/kW)	1,000	700	385
OPEX (% CAPEX)	4	4.57	7.27
Efficiency (kWh/Nm^3H_2)	5	4.9	4.8
Fuel Cell	2015	2030	2050
Lifetime (hours)	40,000	50,000	60,000
CAPEX (€/kW)	2,000	800	500
OPEX (% CAPEX)	2	2	2
Efficiency (% LHV)	50	63	67
Vessel	2015	2030	2050
200 bar	225	225	225

[7] **Data obtained from manufacturer.**

450 bar	1600	960	768
900 bar	2200	1320	990
Compression stage			
120 Nm^3/h (10>450 bar)	2015	2030	2050
CAPEX (€)	300000	240000	210000
OPEX (€/h)	1	0,8	0,7
Electricity demand(kWh/Nm^3)	0,5	0,5	0,5
120 Nm^3/h 450>900 bar	2015	2030	2050
CAPEX (€)	120000	96000	84000
OPEX (€/h)	1,4	1,1	1
Electricity demand(kWh/Nm^3)	0,2	0,2	0,2
120 Nm^3/h (10>200 bar)	2015	2030	2050
CAPEX (€)	1000000	800000	700000
Electricity demand(kWh/Nm^3)	0,2	0,2	0,2
3000 Nm^3/h (30>80 bar)	2015	2030	2050
CAPEX (€)	1000000	800000	700000
Electricity demand(kWh/Nm^3)	0,2	0,2	0,2

Once the investment costs have been estimated, the replacements are considered based on the function hours of each device, allowing the system to introduce the lifecycle of the different equipment. Note that, as far as the time scope is 20 years, equipment as the vessels are not going to be replaced meanwhile equipment as the fuel cells are going to suffer from various replacements as function of the needs of the system.

These replacements are going to be implemented taking into account the price evolution possibilities. On the one hand, the technological advances that are continuously being developed caused a price decrease in the fuel cells, electrolysers and special materials. On the other hand, the usual equipment has fewer chances to decrease its prices, so a growth on them is going to be assumed, based on the inflation. Briefly summarizing, Table 13 shows which components are going to increase, and which ones are going to decrease, based on the information available in [8].

Table 13. Cost evolution trends for the economical assessment.

Genset	Increase
Batteries	Decrease
Renewable energy productor	Increase
Electrolyser	Decrease
Fuel Cell	Decrease
Hydrogen Storage 200 bar	Increase
Hydrogen Storage 450 bar	Decrease
Hydrogen Storage 900 bar	Decrease

Compresor	Decrease

For the operational costs three different situations are considered:

- Transport by helicopter for the diesel gensets of the mountain huts.
- Transport by road by the weak grids markets in Africa.
- Electricity costs without taxes in the on-grid HRS.

According to the electricity and the diesel annual variation, the electricity is supposed to suffer for a price increment which has been assumed as a 1 % per year, at the same time diesel, as far as it is a fossil fuel and is currently losing its fame, will also increase its costs by a 1.5 %, based on the authors assumptions.

For the maintenance costs, these costs are considered separately from the operational costs. This costs are based in the OPEX of each technology obtained from [8] and are shown in the Table 12

In order to obtain a value that will be representative, the total hydrogen produced or energy produced will be divided by the total costs at the NPV, obtaining then the comparison that has been presented in this document.