Final project report (technical and financial)

Deliverable1.7

GRANT AGREEMENT
700359

D1.7 Final Project Report

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Author(s)	Pedro Casero (FHA)
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1. Assessment of objectives of ELY4OFF

The purpose of ELY4OFF is the development and demonstration of an autonomous off-grid electrolysis system linked to renewable energy sources. The PEMWE industrial prototype (50 kW) is directly linked to track the solar photovoltaic power source cold start and rapid response to changes. The demonstration period in a relevant environment (TRL 6) lasted 7 months and took place in Huesca, Spain.

In the next table an evaluation of the objectives established for the project is presented.

Objective	Description	Conclusion
1	Design of an optimized 50 kW PEMWE directly coupled to a solar photovoltaic power source producing over 1.5 tonnes of hydrogen per year for different end uses ensuring cold start and rapid response to changes	Achieved
2	High system efficiency and low cost	Mostly achieved
3	Very high-efficiency cell	Mostly achieved
4	Robustness and safety	Achieved
5	Flexibility for direct coupling to RES	Achieved
6	Durability	Achieved although accurate evaluation at lab is required
7	Communication and Control Capabilities	Achieved
8	Optimized design	Achieved
9	CAPEX competitiveness	Partially ahieved
10	Study of relevant regulations, codes, standards, incentives and examples of off-grid scenarios and end users requirements	Achieved
11	Detailed cost analysis (CAPEX/OPEX), for 50 kW PEMWE	Achieved
12	New business model	Partially achieved
13	Assessment of potential target markets and specific business cases	Achieved

Table 1. Evaluation of the fulfilment of ELY4OFF's objectives

2. Demonstration Phase

The system integrated and commissioned in the previous period was put in operation during the Demonstration Phase which lasted 200 days (started on 11 March 2019. 413 kg of green hydrogen produced until end of September 2019).

Figure 1. Demo-site (electrolyser on left, energy management system on right)

Figure 2. Aerial view of the demosite in FHa's premises in Huesca: 62 kWp of PV, 50 kW PEMWE, energy management cabinet

The final configuration of the Hybrid Storage System is composed by: 36 kWh lead acid batteries (between 20 to 36 hours of autonomy depending on the season), 4.5 kW stationary low temperature PEM fuel cell to cover safety loads when the lead acid batteries are discharged, and a H2 capacity of 7 kg at low pressure tank (20 bar), and 23 kg at high pressure tank (350 bar).

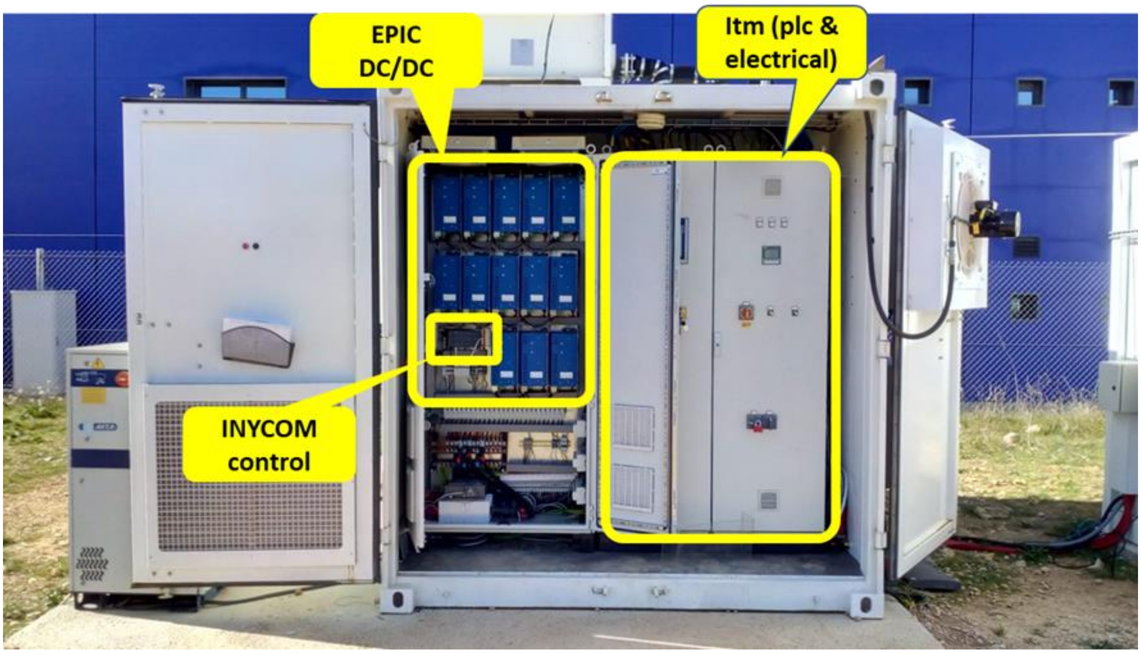

Figure 3. Inside view of electrolyser electrical cabinet

Figure 4. Inside energy management control cabinet

The initial phases of the demonstration allowed understanding the behaviour of the system and to prepare it for specific testing campaign. 7 indicators were selected for specific tests during the demonstration period: Efficiency at system level, Efficiency degradation, Hot start (min to max power), Cold start (min to max power), Minimum part load, Ramp up, Efficiency of PSU, Power usage of auxiliary equipment and Power of control system when off.

The main facts during the period are summarized below:

- The demonstration started on 11th March 2019.
- The demonstration ended on 30th September 2019 (203 days)
- No safety incident was reported.
- Total accumulated hydrogen production was 413 kg.
- The maximum production of hydrogen in one day was 5.9 kg (5/09/19)
- The maximum load reached in the stack was 82.4% (10/09/19)

The weekly production of H2 during the period is presented below:

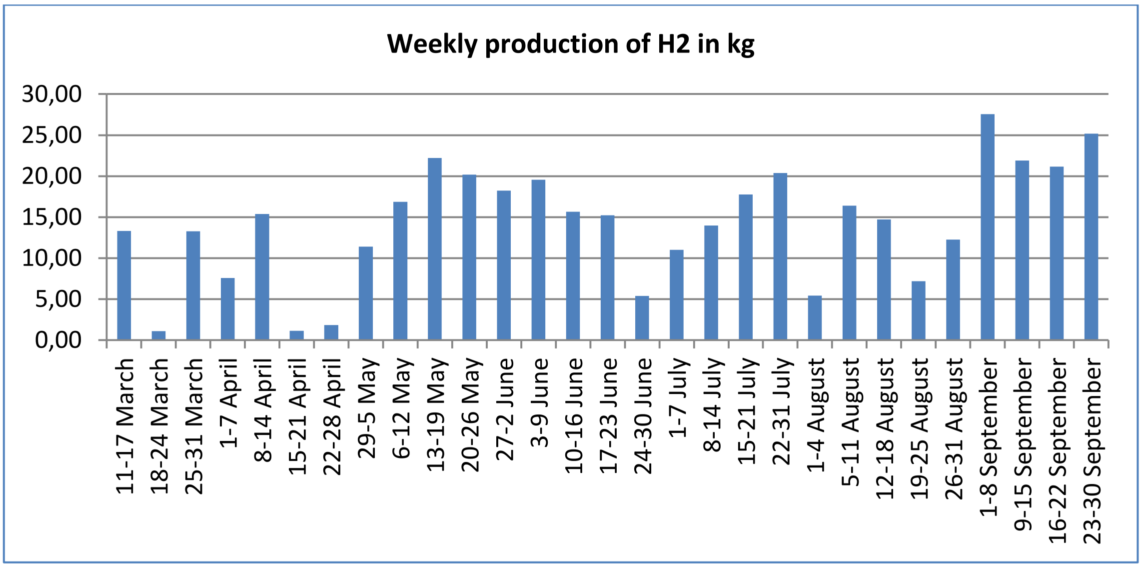

Figure 5. Weekly production of H2 during demo phase

As an example of the operation of the system, the graph below (5 September 2019) shows the power to the stack (blue line) in a good weather day. The yellow line shows the operation of the batteries, and a negative value means that they are being charged. Finally the BoP consumption is depicted in black and the SOC of the batteries in red. We can see that there is a base load of around 6 kW, and peaks reaching 15 kW, derived from the intermittent operation of the H2 purification unit mainly and other elements.

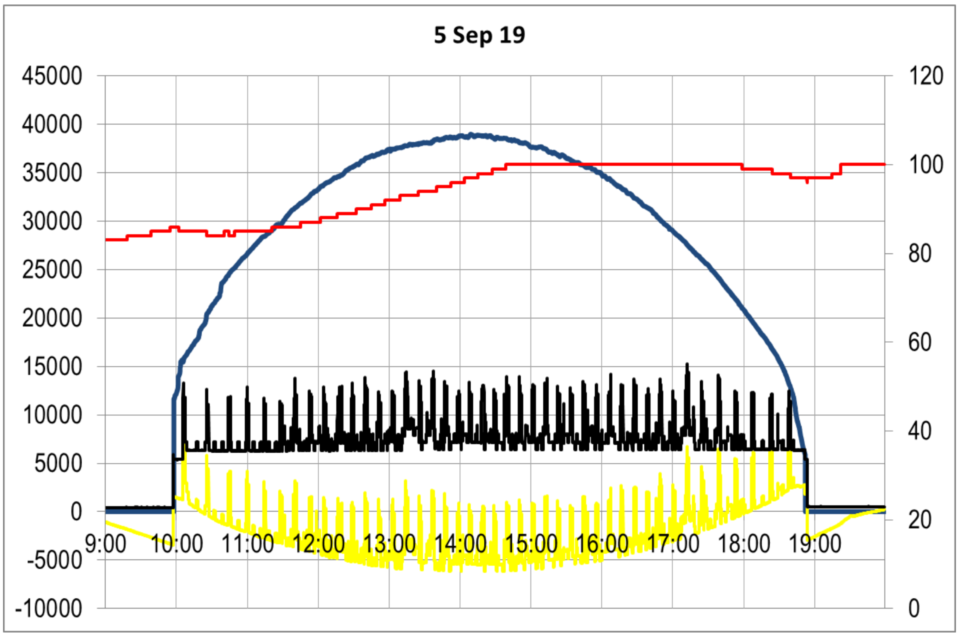

Figure 6. Operation of ELY4OFF system in a good weather day

3. Lessons learnt during Demonstration Phase

- A great effort was done to adapt the electrolyser BoP to the variable solar profile. But it can be improved in many aspects, like the conversion of the entire consumers to work in DC.
- Unfortunately a thin MEA could not be finally tested due to time restrictions. But results were promising.
- Many modifications were applied to the ely's control system. Some others have been identified but could not be tested in the scope of the project. For example the transition between IDLE/STANDBY/OPERATION requires optimization.
- The size of the system (50 kW) makes that BoP consumption is disproportionately big. Further research for larger units (even up to 1 MW) should be pursued.
- The DC/DC converters have shown magnificent robustness and performance, exceeding the target efficiency. Even so, some aspects were identified to be further investigated.
- The estimation of power available for starting-up the system requires further refinement. It does not affect significantly on the amount of H2 produced but it is an area of improvement.
- With the experience gained with the energy management configuration tested (10 strings to stack, 3 strings to BoP), the original configuration (with all the strings connected) is considered to be a better solution. With the one tested during the demo there was energy wasted at some moments when the batteries were fully charged. This would be (probably) avoided in the other.
- The storage of energy in batteries tested does not allow feed the stack for bringing forward the hydrogen production in a day with good weather forecast. Such flexibility would provide helpful insights.

- The availability of the system improved as demonstration period progressed. The knowledge gained in several aspects of the control procedures, joined to the tuning of many parameters made that the amount of alarms causing shutdowns reduced dramatically. More modifications are identified that would increment even more the availability, which is an essential issue to consider in an off-grid system.
- It is of utmost interest to continue the demonstration during extreme weather conditions. It would allow stressing the system to limits that would offer valuable insights on consumption of the frost-protection system specially and would offer a robust support to deploy the system in other locations.
- The optimal balance between the size of the PV field and the stack capacity is not trivial. Considering the low CAPEX of PV technology it seems advisable to oversize it in order to bring the electrolyser to 100% load during a good period of the day. But the combination with electrochemical storage seems also reasonable and would allow even to keep the system operating continually.
- The ELY4OFF system ends in the production of H2 at 20 bar. Its integration with other elements (compression, storage, final application) would be an interesting challenge for the overarching control system.

4. Main challenges during the project

a) ITM tried to develop a thin membrane but short circuits appeared after some hundreds hours of tests so a commercial thicker membrane was selected instead. The efficiency was lower than the thin one, but there was not enough time in the project to keep trying.

b) We experienced delays during fabrication and assembly, due to several reasons. Finally the accumulated delays forced to extend the execution period.

c) I already mentioned the energy management configuration finally tested that was not the originally devised.

d) Finally it's a fact that during the demo period the extreme weather conditions were not covered. Tthe consortium has come to an agreement to follow the demonstration during some more time to gather information on the behaviour of the system also during winter time.

5. Exploitation Plan

a) **Unique selling points**: Dynamic and fast answer H2 production, Excellent H2 purity for any purpose, Self-sufficient system up to several days, Scalable up to 10 MW

b) **Strategy Plan**: 6 exploitable results (ITM: 3, EPIC: 1, INYCOM: 1, FHa: 1), 3 business cases elaborated: off-grid installation, Power to Gas, and mobility,

c) **8 target markets identified**: Telecoms, Power to Gas, isolated areas, back-up systems in weak grids, HRS, fertiliser production,

6. Business cases

Three main applications were modelled and simulated:

- Isolated site electrification with specific business cases located in Tenerife (Spain) and Edinburgh (Scotland)
- Gas grid injection with business cases located in Millau (France) and Shetland Islands (Scotland)
- Mobility application with business case located in Miallau (France) and Hofn (Iceland).

For each of the simulated business cases, the levelized cost of electricity (LcoE) or the Levelized cost of hydrogen (LcoH) were computed based on a set of techno-economic hypothesis.

a) Business case #1: Isolated sites electrification

In this work, the only considered renewable power source was photovoltaic. Work carried out especially allowed for the observation of the influence of the following hypothesis:

- The location of the installation: Tenerife vs. Edinburgh
- The electrical load to provide
  - 1 and 4 kW steady load
  - Home variable load
- The available PV surface

Simulations and techno-economic calculations allowed for the comparison of optimal LCE (Levelized Cost of Electricity) for the following system configurations:

- PV-Battery
- PV-Battery-H2
- PV-Diesel generator
- Diesel generator

Figure 7 gives a general overview of computed LcoE for simulated isolated configurations. Observed LcoE range is from around 500 €/MWh to 5000€/MWh. Although these values might seem high, it can be explained (i) by the small size of the considered system (< 5 kW peak power) and (ii) by the strict autonomy necessity leading to a massive oversizing installed PV surface. This second point is illustrated by a lorge amount of unused PV, up to more than 75% of total PV energy in least favorable cases.

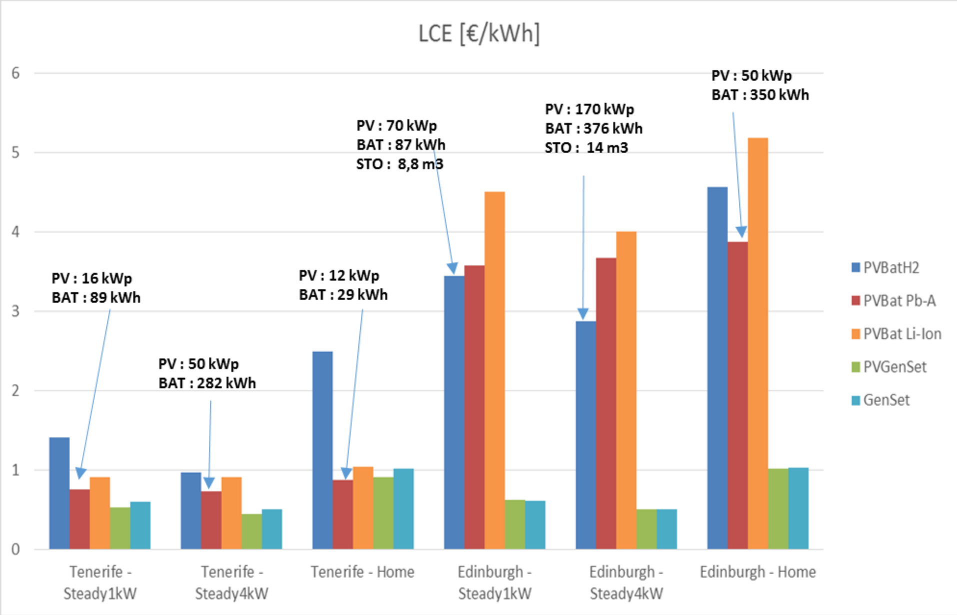

Figure 7. Overview of LcoE for electrification application

The evaluation of this first business case using ODYSSEY software showed that off-grid production of hydrogen from PV power may compete with PV-Battery solutions when seasonality is important, PV is limited and electrical load remains high during nights.

However, competing with diesel-based solutions remains difficult even with diesel fuel price as high as 3€/liter.

In situations when PV is abundant and less seasonal (South of Europe typically) PV-BAT systems seem more economically attractive than hybrid solutions associating batteries and electrolysis larger than 10 kW.

b) Business case #2: Hydrogen injection into gas grid

For this second business case, simulations were performed in order to target the main following purposes:

1. Compare different configuration of the system at an economic level, that is to say minimizing well-chosen indicators such as the Levelized Cost of Hydrogen – Grid injection based (LcoH2 expressed in €/kg)
2. Evaluate the sensitivity of the location chosen, the type of RES used, the size of the system and the main hypothesis set on the economic results obtained.

24 different configurations were simulated. These are defined by:

a) The type of RES: solar photovoltaic, onshore wind, offshore wind and hydro energy
b) The location: Northern Europe (Shetland Islands, UK) and Middle-Southern Europe (Occitanie region, France)
c) The size of the ELY4OFF installation: 4 model of electrolyzer with a 56, 200, 500 and 1000 kW maximum stack power

Figure 8 and Figure 9 illustrate the Levelized Cost of Hydrogen produced in both locations for considered renewable power source. Range of LcoH from 4.5 to 50 €/kg was observed and strong impact of (i) location (ii) renewable source and (iii) size of electrolyzer appears.

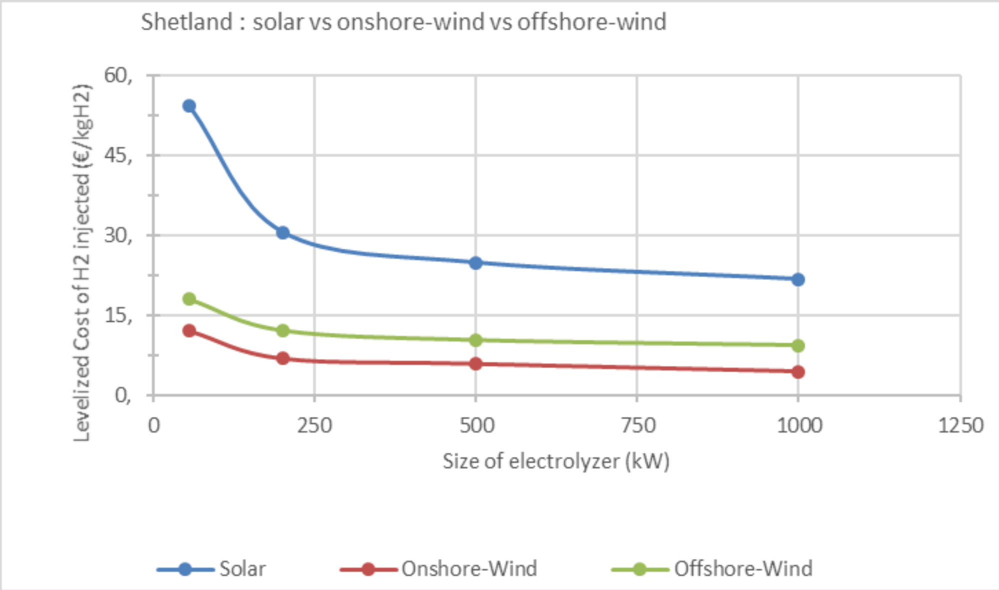

Figure 8. Computed LcoH for Shetland Islands business case

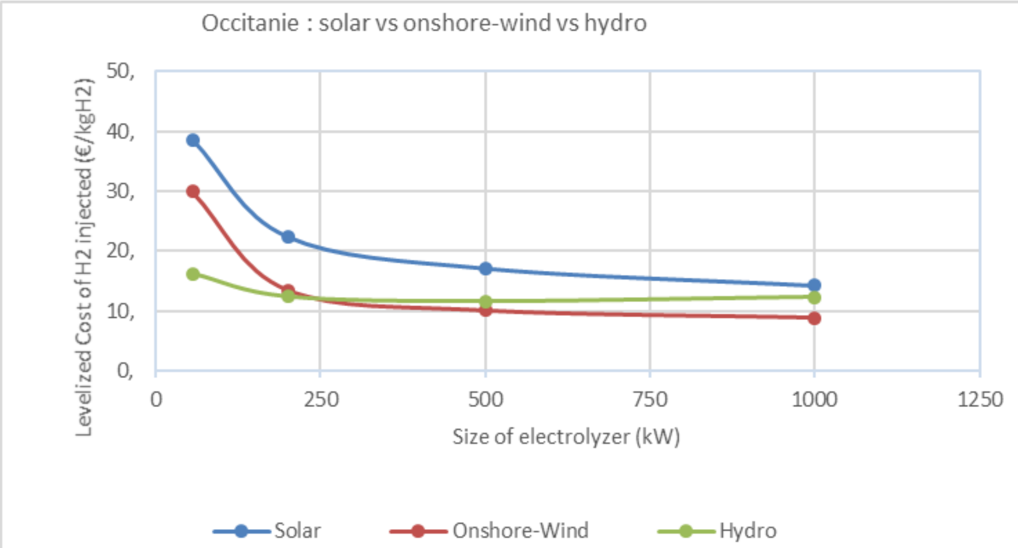

Figure 9. Computed LcoH for Millau business case

The main lessons obtained were:

- ✓ The onshore wind configurations are always the most profitable (LcoH2 reaches 4.45 €/kgH2 in the best case). They may compete with biomethane injection costs (Feed-in-Tariff reaches 5.5 €/kg in some European countries) but not with the natural gas price today (0.91 €/kg in hydrogen equivalent) although CO_2 emissions comparison should be taken into account in this case.
- ✓ Sizes of electrolysis stacks above 200 kW lead to reduced cost of produced hydrogen.

- ✓ The system location and especially the meteorological conditions (insolation, wind) have a significant influence on the LcoH2: for MW stack size, LcoH from PV is reduced by 60% in Millaud compared to Shetland and LcoH from wind is divided by two in Shetland compared to Millau.
- ✓ The offshore wind energy generation with floating turbines lead to LcoH only slightly higher than for on-shore wind power production. This option needs to be studied deeper and could be a good opportunity with the expected significant deployment of wind turbines in the North Sea and the decommissioning of natural gas rigs.
- ✓ Almost all the optimization results in ODYSSEY leads to an oversizing of the RES (up to 14% of energy is wasted for smallest system) maximizing the H2 injected into the grid as an economic optimum but it increases the amount of energy unused and does not always match with a realistic situation in terms of technical constraints.
- ✓ As the CAPEX of the RES have a significant share in the total costs of ELY4OFF (between one third and three quarter), these parameters are the most sensitive on the LcoH2 calculation. The LcoH2 could be influenced at a value between 5 and 15% depending on the cost estimation.
- ✓ Finally, cost of gas injection station into the grid lead to a 30% increase of LcoH for 1MW scale electrolysis system powered by on-shore wind installation in Shetland.

c) Business case #3: Hydrogen mobility

In this third business case, dedicated to mobility applications in isolated zones, different configurations of the ELY4OFF system were simulated to determine the influence of the following parameters on the economic results:

- The type of renewable energy: solar photovoltaic, onshore wind and hydro energy.
- The location: Northern Europe (Iceland) and Middle Southern Europe (Millau)
- The type of end user's H2 loads: captive fleet of buses or cars with various refueling intensities and frequencies.

After a modeling phase on the ODYSSEY software, the minimization of the Levelized Supply Cost of Hydrogen (LcoH2, [€/kg]) for each configuration studied was the main objective of the simulation task.

Figure 10 and Figure 11 illustrate the calculated LcoH (including refueling station) for different configuration in France and Iceland.

- In Millau, it can be observed that LcoH ranges from 200 €/kg for smallest PV installation to 35€/kg for larger hydro and wind installations.
- In Iceland, LcoH ranges from 260 €/k for smallest PV installation to 34€/kg for larger wind installation.

Computed levelized cost of hydrogen might seem high for simulated business cases. It is important to note that for higher LcoH, the cost of hydrogen refueling station is very important (up to 60% of the total cost in some cases). The necessity of hydrogen production autonomy for a given hydrogen load also leads to an oversizing of renewable source (40 to 70% of renewable power is not used) and hydrogen storage to satisfy the load.

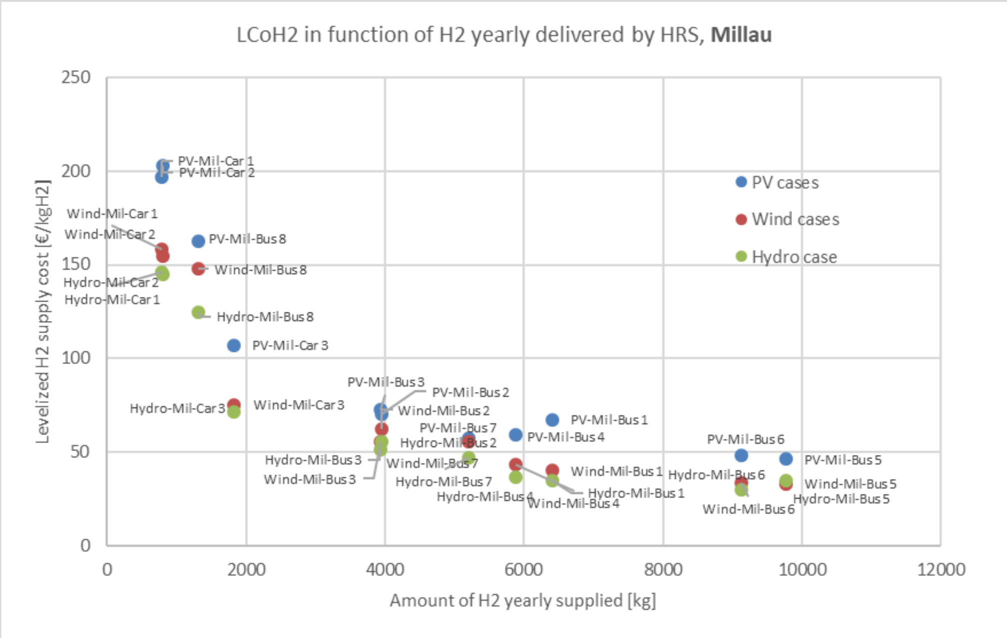

Figure 10. Computed LcoH in Millau (France) for3 different renewable power sources configurations

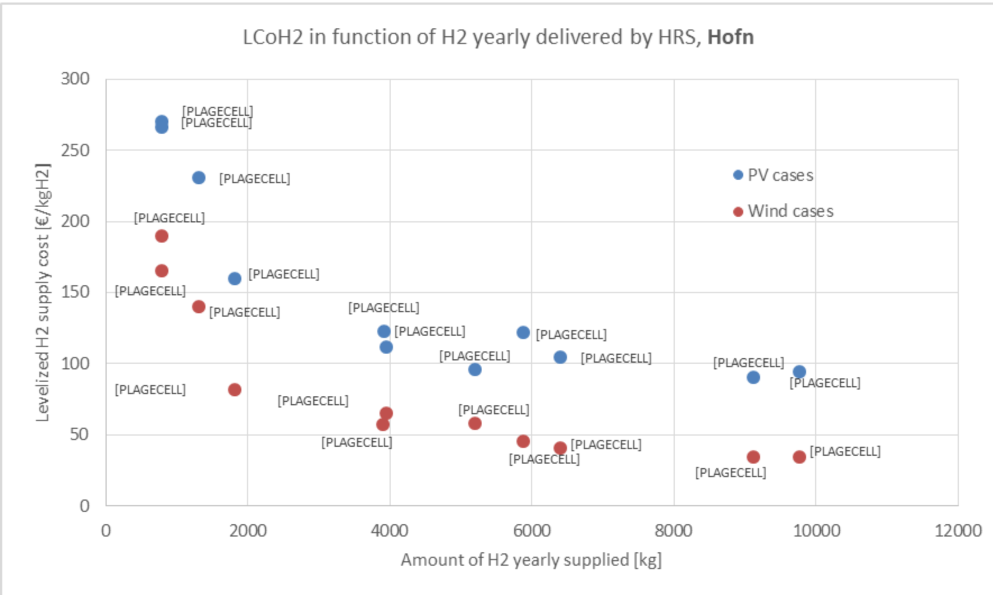

Figure 11. Computed LcoH in Hofn (Iceland) for different PV and wind configurations

The main lessons that can be learnt thanks to this study are the following:

- ✓ The best configurations from an economic point of view are those for buses powered by wind energy (Wind-Mil-Bus5 with a 33.08 €/kgH2 LcoH2, including refueling station). Indeed, larger is the amount of H2 supplied (typically for the configurations bus 5 or bus 6), better is the result. This remains 3 times more expensive than the currently theoretical acceptance price at the H2 pump (around 10 €/kgH2).

- ✓ The wind energy gives better results than the PV in the 2 locations studied. The difference between economic results from wind and solar energy is more significant in Iceland than in the south of France. This was expected considering the difference of the yearly capacity factor of each RES in these 2 countries.
- ✓ Electrical cars with a fuel cell range extender give better results on average than pure H2 vehicles for performing the same delivery service.
- ✓ Simulation shows that there is no significant influence of the refueling schedule on the economic results.
- ✓ The configurations tested and optimized lead us to a sizing in the range [10-400] kW for the electrolyzer stack power ([10-80] kW for car cases and [30-400] kW for the bus cases.
- ✓ The ELY4OFF system's sizing strongly depends on the power generated by the RES, more on irregular meteorological events (e.g. absence of sun during 2 months in Iceland) than on the yearly capacity factor of the RES considered. For example, the size of the H2 reservoir has to be increased (over 100m3) for a seasonal storage at high pressure to counterbalance the low insulation, raising problems about safety or legal acceptancy.
- ✓ All the configurations lead to a high amount of unused primary energy (between 40 and 75%) that could be valorized in other applications. The sale of the electricity in excess contributes to lower the LcoH2 only at values between 5 and 13%.
- ✓ The most sensitive parameters identified on the results obtained are the CAPEX of the equipment: the HRS's CAPEX has a larger influence than those for the RES and the electrolyzer.
- ✓ Hydrogen mobility for the niche application considered gives today economic results quite different from those expected from a classic mobility segment: costs are about 3 times higher for buses shuttle services and 7 times for cars captive fleets comparing with the diesel mobility. However, these 2 applications could be relevant in well-chosen isolated places where the supply costs of fossil fuel or electricity is expensive.

Main conclusions:

Based on the modelling and simulation work carried out in task 6.6, it was observed that, although cost of full off-grid hydrogen remains high, each of the three evaluated applications from a techno-economic point might be interesting under certain conditions. Off-grid hydrogen may represent benefits compared to competing technologies:

- ✓ For electrification of isolated site with high seasonality of renewable power is observed;
- ✓ For gas grid injection when renewable power factor is high and gas grid constraints are limited;
- ✓ For mobility when renewable power factor is high and low carbon mobility is valued.

7. Dissemination

Concept	Value
Organisation of Workshops	1
Press releases	21
Scientific papers	4
Flyer	1
Social Media	67
Website	1
Participation to a Conference	13
Participation to a Workshop	1
Participation to an Event other than a Conference or a Workshop	1
Video/Film	1
Pitch Event	1
Trade Fair	1
Participation in activities organized jointly with other EU project(s)	1

4 ***scientific papers*** and proceedings have been accepted for publication and 3 of them are available on-line (open access).

Date	Publication	Format	Name of publication
Oct 17	Iberconappice	Proceedings	Sistema Híbrido de Almacenamiento (H2 y baterías) para instalación aislada. *Lorién Gracia (FHa), Pedro Casero (FHa)* Pages 227 – 231 https://appice.es/Congresos/APP-Iberconappice2017.pdf
Mar 18	EHEC 18	Proceedings	Use of hydrogen in off-grid installations. A techno-economic assessment
Ago 18	CSMH 18	Proceedings	Sustainable and efficient off-grid production of Hydrogen. Demo Project on-going in Spain *Rubén Gálvez (EPIC POWER), Logan López (EPIC POWER), Estanis Oyarbide (EPIC POWER), Lorién Gracia (FHa), Pedro Casero (FHa), Edgar Bueno (FHa)* http://hidrogeno.org.mx/wp-content/uploads/2017/07/ISSN-2448-71202018.pdf
Nov 18	Energies	Special Issue	Use of hydrogen in off-grid locations. A techno-economic assessment *Lorién Gracia (FHa), Pedro Casero (FHa), Cyril Bourasseau (CEA) and Alexandre Chabert (CEA)* https://www.mdpi.com/1996-1073/11/11/3141

The **workshop** organized in Huesca was intended to promote and facilitate a first exchange of views about the integration of Renewable Electricity through applications of WE technology. The event provided a forum to discuss the latest technological innovations. Key discussions were involved sharing challenges and opportunities related to hydrogen production from water electrolysis. The workshop also provided the best platform to explore potential collaborations. The key topics at the workshop were:

- Optimization of H2 production cost based on electricity source (PV, wind, grid)
- How off-grid affects to standard on-grid configuration from control perspective
- Current regulation barriers and recommendations to overcome them
- Power to H2: elements of value (values to the power grid, values to the gas grid, values to decarbonized industry, values to the UE Economy, etc…)
- R&D needs: demonstration at MW scale, reliability, durability, cost reduction, efficiency, mixing technology (and regulations)
- Harmonization testing protocols: grid balancing vs. off-grid

A picture of the visit to the demo-site is included below

Figure 1. Visit to the demo-site during Workshop

Around 50 participants attended the workshop, who gave a very positive feedback.

Most of the attendees to the Workshop were end users (60%) mostly from the renewable & environment industry (34,5%). Apart from ELYNTEGRATION, 3 other FCH JU's projects were invited (HYLAW, HPEM2GAS and H2FUTURE).

8. Final remarks

The project outcome has been satisfactory and the majority of the objectives were achieved, As consequence of it the **partners agree to continue the testing** of the system after the end of the project.

Strict off-grid conditions lead to significantly higher cost of electricity (LCoE) or hydrogen (LCoH) but may be, in the future, necessary to valorize important renewable power potential and guarantee low carbon hydrogen production for various applications.

Work carried out in the project shows that Off grid electrolysers can hardly compete economically at small (kW) scale. Further RD&D work must be undertaken at MW scale with a focus on regions exhibiting high seasonality and by employing both wind and solar power sources.

It is also interesting to note that if the required hydrogen system consists primarily of a large electrolyser then the predicted levelized cost values are not too high. However, when the H2 application requires several other technologies as well as an electrolyser then the LCOH or LCE values are extremely high, due mainly to the high system capex. R&D work on system components such as gas grid injection or refueling stations must be carried out to contribute to cost reduction.

Due to the diversity of applications and the impact on cost of optimized design, it is important to note that manufacturers should not simply make a 'one size fits all' solution for off grid hydrogen systems but adapt system to specific application.

Considering an off-grid implementation in practice means that the cost of connecting to the grid would be very high. So there is an avoided cost of grid connection and of grid fees, which theoretically contributes to reduce CAPEX and OPEX costs, but was difficult to assess in this study.

Finally, it is important to bear in mind that that because of the scale of the ely4off hardware demo development, the main focus of the project was on assessing kW scale deployments for early markets. It is recommended that further attention be given to the economics of multi-MW and GW scale off-grid hydrogen application. Indeed, since the project started new positions were taken on green hydrogen production at massive scale by Australia, Holland for the North Sea region, Saudi Arabia, with further potential contributions from Chile, North Africa, Norway, Iceland etc. Increase in hydrogen components manufacturing will also lead to large reduction of costs for hydrogen application that was not considered in this study.

In this work, considered hydrogen is fully green as it is produced from renewable energy only. Such hydrogen is of the highest quality in terms of decarbonisation potential as it avoids uncertainties concerning the actual carbon footprint of hydrogen produced by grid electricity, or by SMR+CCS. Green hydrogen appears to be more expensive but its potential in achieving zero emissions by 2050 and the associated value should be considered