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P2P systems for Canada off-grid communities

A comparison with EU demo projects

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The electric system of Canada's remote off-grid communities faces several challenges, including high generation costs, limited access to fuel, cold climate, aging diesel generators, high variance of electric demand, environmental risk, limited generation capacity. A variety of solutions exist: each community should leverage on its strengths to develop the most appropriate. In this work a hybrid stand-alone system including hydrogen as energy storage is studied. Such system is applied to two Canadian case studies to see the effect on the levelized cost of energy. The current thesis is divided into five sections. Section one outlines the framework where this work collocates, describes the goal of it and presents a literature review of similar systems. Moreover, a description of remote communities across the Country is provided. Sections two and three detail the two case studies developed, Paradise River and Colville Lake communities. A techno-economic analysis is carried out step by step, from load modeling to simulation of the system. Following the technical study, the economic study is aimed to LCOE assessment for different alternative scenarios. Sensitivity analysis on some parameters and comparisons among alternative options are developed as well. Environmental footprint is discussed in Section four, which provides an overview of the benefits such sustainable energy alternative can offer in terms of reduction of pollutant emissions. Section five resumes the results of the analyses comparing them with other Canadian and European studies. Specifically, a comparison with REMOTE EU project is carried out. In this part an investigation on regulatory and social aspects is also provided. The work, developed in collaboration with Ontario Tech University (former UOIT), aims to bring out the highlights of a sustainable hydrogen-based system which is overall non competitive with traditional solutions but can reveals attractive in special contexts such as remote communities.

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Section 1 - Overview

1.1 Introduction

Paris, June 28th. Météo-France, the French state weather forecast, reports a temperature of 45.9 °C in Gallargues-le-Montueux, in the south of the Country, beating the previous record of 44.1 °C hitted during the heat wave of 2003. It's the first time a temperature exceeding 45 °C is recorded in France, as confirmed by the meteorologist Etienne Kapikian [1].

Antarctica, February 14th. A study led by Anders Levermann estimates the future sea level contribution of Antarctica from basal ice shelf melting up to year 2100. Combining 16 ice sheet models, the team found that if carbon emission go largely unchecked and temperatures rise by almost 5 °C by 2100, Antarctica would have more than 90% likelihood of causing sea level rise between 6 and 58 cm, with median value 17 cm, by the end of the century. Such increase is three times bigger than what predicted in the 20th century from all sources [2].

The above-mentioned examples are just two of climate change effects we all are experiencing in this age. The increase of CO_2 emissions has a primary role in global warming, as confirms NASA temperature trend [3], which sees nineteen of the 20 warmest years (starting from 1881) occurred since 2001, with a annual average anomaly of 0.98 °C[1] in 2019. A recent report by EIA (Energy International Agency) assesses that after a period of stability in 2014-2016 years, CO_2 emissions from fuel combustion started rising again, reaching the historic high of 33.1 Gt released in 2018 [4]. The rate of growth in one year, 1.7%, is the highest since 2013 while the average growth since 2000 amounts to 44%. In 2018 the global average concentration of CO_2 in the atmosphere averaged 407.4 ppm, increasing by 2.4 ppm since 2017. The preindustrial level ranged between

[1] A temperature anomaly indicates how much warmer or colder than the long-term average a unit of something is.

180 and 280 ppm. According to the report, the increase in emissions was driven by higher energy consumption resulting from a robust economy, as well as from weather conditions in some areas that led to increased energy demand for heating and cooling. World's energy outlook by EIA [5] unveiled that energy consumption grew by 2.3% in 2018, amounting to 328 Mtoe[2] in 2018. Such trend confirms a clear relation between the increase of energy consumption and the amount of CO_2 emitted. Such demand is covered by fossil fuels for 70%. Renewable energy sources (RES), meeting 81 Mtoe, play a key role toward a clean energy system. Nevertheless, even growing at double digit pace and accounting for almost one quarter of energy demand growth, it is not still fast enough. There are plenty of ways to produce green energy, but solar and wind energy represent of course the roads with highest potentiality to achieve the goal of sustainable energy production and to meet Paris agreement, which long-term goal is to pursue efforts to limit the increase in global average temperature to 1.5 °C, aiming to reduce substantially the risks and impact of climate change. Renewable power capacity is set to expand by 50% (1200 GW) between 2019 and 2024 led by solar PV which accounts for almost 60% of the expected growth. These numbers confirm the interest in renewables to replace fossil fuel based systems in the energy sector today. It's well known that they are also non-continuous energy source, since the electric production depends on atmospheric conditions, which are variable and unforeseeable. The intermittent nature of RES makes the use of energy storage crucial in making alternative energy-based systems feasible, in order to cover the load when the source is not available and exploit the excess when there is surplus. Figure 1 clarifies the role of energy storage.

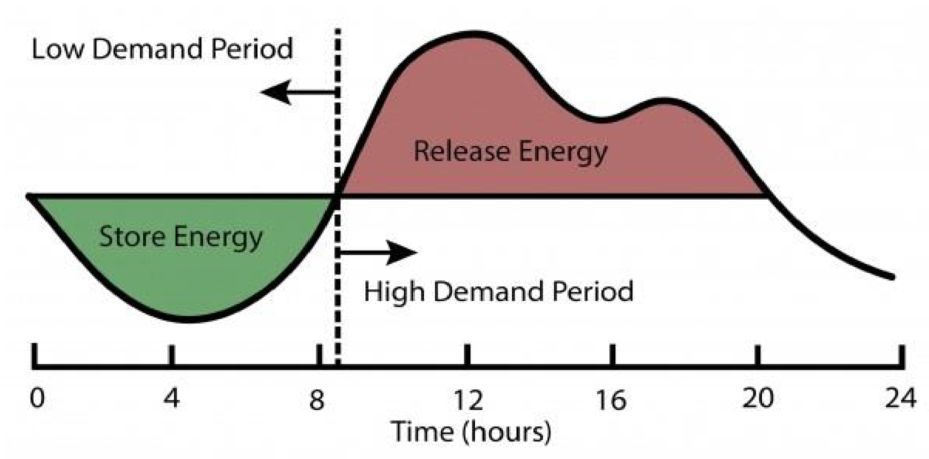


Figure 1 Usefulness of energy storage under intermittent conditions

[2] Tonne of oil equivalent, unit of energy. 1 toe= 41.868 GJ= 11.63 MWh.

IEA defines 2018 “a bumper year for energy storage”, as annual deployment nearly doubled from 2017 to reach over 8 GWh [6]. A key technology trend has been to co-locate renewable energy production facilities with energy storage assets, improving the economics of the projects. Lots of storage technologies exist nowadays, including thermal, magnetic, electrochemical, mechanical, chemical storage. Concerning the last one, hydrogen represents an excellent way to perform long term storage, by means of a flexible fuel producible from energy surplus and convertible into electric energy through fuel cells. Hydrogen has been an integral part of the energy industry since the mid-20th century. Demand for hydrogen has grown more than threefold since 1975 and rises year by year, accounting today to 70 Mt_{H2}/year [7]. In energy terms, this means around 330 Mtoe. The existing market for hydrogen builds on its remarkable attributes: it is light, reactive, has high energy content per mass. Particularly, today’s interest in the widespread use of hydrogen rests largely on two aspects: the possibility to use it without direct emissions of air pollutant and the possibility to produce it from a diverse range of low carbon sources or in totally green way. Nevertheless, the major part of hydrogen is supplied from fossil fuels; as a consequence, hydrogen is responsible for CO_2 emissions of around 830 Mt_{Co2}/year. Producing hydrogen from water electrolysis is a clean-burning and sustainable process, completely zero-emissions if electric energy required by electrolyser is renewable [8]. The efficiencies of such systems range between 60% and 80%, and with declining costs for renewable electricity, in particular from solar PV and wind, interest in such form of hydrogen is growing and gave birth to several projects in recent years. Large size projects, required to demonstrate accelerated scale-up, are already announced and a 20 MW project is under construction right in Canada [9].

The coupling between RES and hydrogen as storage (power to gas systems) has been studied for a long time, as confirms the large number of papers and studies related (examples in [9][10][11][12][13]). Using hydrogen as storage for renewable sources has several advantages, such as the possibility to exploit energy excess performing a seasonal storage, not achievable with traditional batteries, in a zero-emission way. This allows to balance seasonal variations in electricity demand. Of course, drawbacks are not lacking: hydrogen technologies are still expensive and efficiencies are quite low since the process requires different steps of energy conversion.

A special situation where fossil diesel fuel is used as main energy source is that of off-grid communities. The remote localization of such villages makes the connection to the electrical grid expensive and technological unachievable [14]. Diesel generators represent in these cases the only way to provide basic services to people, although harsh consequences on pollution and energy efficiency. Fuel cells can help to provide back-up for power outages and access to electricity for such off-grid villages or buildings. The case studies carried out in the present work refer to Canada, where vast distances separate remote communities from their neighbours. Since remote communities are not connected to either natural gas infrastructure or the North American electricity grid, they must produce their own energy by burning diesel fuel (derived from oil) to heat their homes and buildings, and to power their small-scale electrical microgrids [15].

In the annual "G20 Brown to Green Report" developed by Climate Transparency, a partnership composed of experts from research organizations and NGOs from the majority of the G20 countries, a review of G20 climate actions is provided, providing detailed information about emissions, climate policies and impacts of climate change through adequate indicators. In country profile section [16], the report states that Canada has the highest energy supply per capita in the G20 (340 GJ/capita, G20 average 98 GJ/capita, with an increasing trend over last years). Moreover, it is the 3rd most energy-intensive economy in the G20. At the same time, energy related CO_2 emissions are rising further, which is not in line with the 1.5 °C pathway. GHG emissions per capita increased by 17% between 1990 and 2016 (despite the trend is slightly decrescent over last 5 years) and today amounts to 18.9 t_{CO2e}/capita versus 7.5 t_{CO2e}/capita of G20 average. The document assesses that the government's climate targets for 2030 and 2050 are not in line with a 1.5 °C pathway, indeed fossil fuels represent still around 76% in Canada's energy mix. Despite the carbon intensity (CO_2 emitted per unit energy) has remained quite stable over recent years (amounting to 47 t_{CO2}/TJ, versus around 60 t_{CO2}/TJ of average G20) strong effort are required to become 1.5 °C compatible.

Most of Canada's emissions come from the energy sector, and the adoption of clean technology to remote communities could be the opportunity for improving environmental scenarios. Canada's plan to address climate change and grow the economy is "Pan-Canadian framework" document [17]; reducing reliance on diesel in Indigenous and remote communities is one of the steps individuated in the document towards a clean growth economy and support such communities in adopt and adapt clean technologies is one of the action foreseen. In remote communities, energy consumption is much higher than the Canadian average, and 70% of them rely on inefficient diesel generators to produce electricity [18]. This means more than 90 million litres of diesel fuel consumed every year for electricity generation (equivalent to 36 Olympic size swimming pools) and two/three times more for heating. Clean energy investments targeted at indigenous, remote and rural community are on the agenda and go through innovative and free emissions solutions.

1.2 Stand alone systems with hydrogen storage – goals of the work

As mentioned in the introduction, a stand-alone system is the only viable option when power is required and no grid connection exists. In the case of off-grid communities, the most spread and easy choice is the use of diesel stationary generators to supply energy. Diesel generators are a well known and mature technology, they are reliable, easily adjustable and not expensive. On the other side, they have some disadvantages which are emphasized when intended for remote communities. These include: polluting emissions, noise, frequent maintenance required, low efficiency. In addition, considering the applications to remote areas, other aspects must be considered. First of all the power generation cost, which turns out to be significantly higher than easy accessible places. Transportation of fuel in such localities, in fact, is often harsh and sometimes not possible in conventional ways. This is the reason why fuel cost in such localities is usually higher than other area. A crucial problem for diesel generators of remote communities is the large difference between peak power demand and average energy demand. The rated power of selected generator should be based on peak power to sustain load. However, in that situation the efficiency drops (it is inversely proportional to rated power) and it will consume large amount of fuel, emitting more greenhouse gases [19]. The traditional system just described is depicted in figure 2.

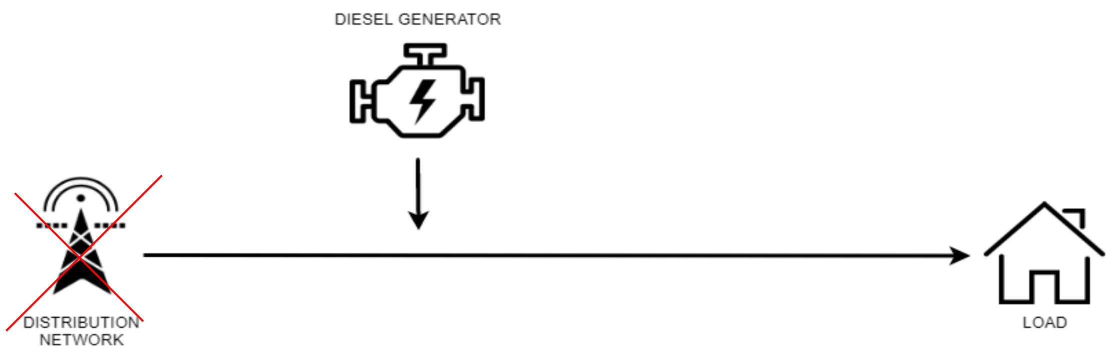


Figure 2 Current solution

Overview

Goal of this work is to analyze the performances of a renewable system (shown in figure 3) which implements the P2P (Power to power) paradigm, that is the conversion of renewable power sources in other means (chemicals, fuels) able to produce power again. This allows the displacement of energy production and thus the possibility to store the energy surplus and cover the energy deficit. Actually, such issue could be accomplished using an electrochemical battery able to store energy surplus from RES, but this can perform only a short-term storage, e.g. between day and night. The P2P system in this work envisages to use energy not immediately required by the load to produce hydrogen in an electrolyser, store it in a tank to be used as fuel producing power in a fuel cell when needed.

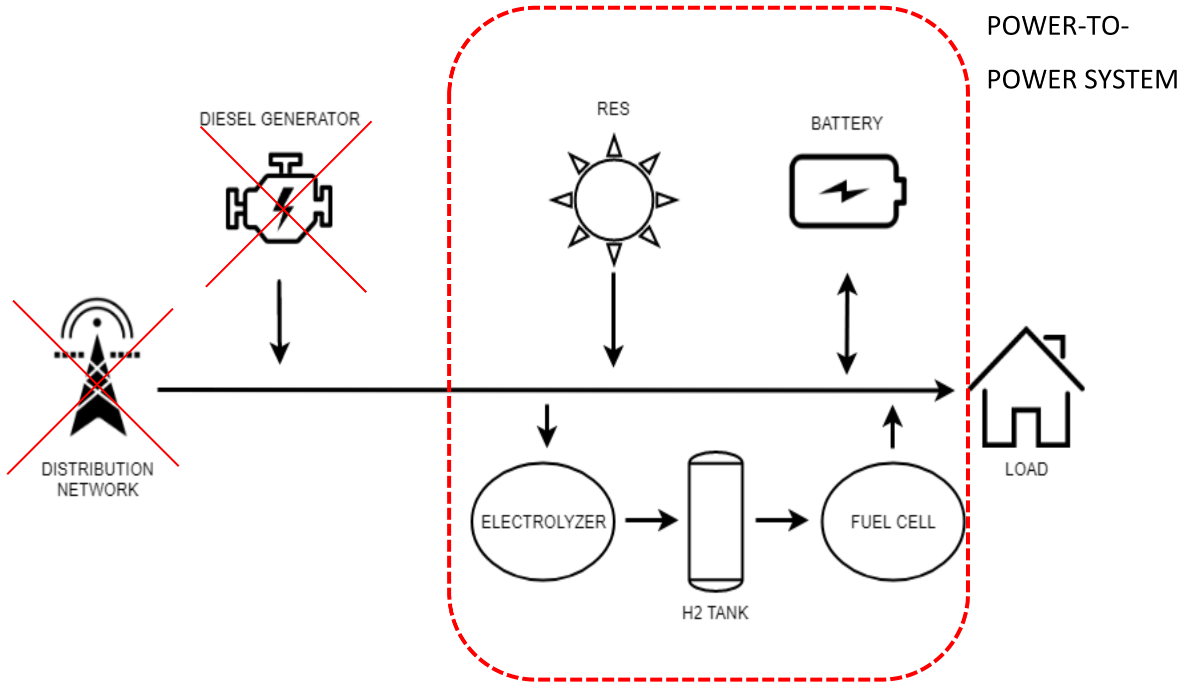


Figure 3 Proposed solution

The proposed system includes one or more renewable power sources, a storage system comprehending a traditional electrochemical battery (optional), a H_2 tank, an electrolyser that receives energy surplus to produce hydrogen and a fuel cell that use the hydrogen stored to produce electric energy when required.

The different combinations will be analysed under both the technical and economical point of view considering different scenarios.

1.3 Stand alone systems with hydrogen storage – literature overview

The number of published works about H_2 based stand alone systems became significant in around 2010 to increase considerably year by year. Most of these papers concerns the application of such systems to domestic users or isolated building, because of smaller scale and easier collection of data about load. An overview of literature findings is displayed in table 1.

Silva et al. (2013) [20] carried out a study for an isolated community in Tocantins, Brazil, getting to a LCOE of 1.21 €/kWh for the H_2 based system and concluding that using traditional battery together with PV is the best option. Das et al. (2017) [21] made a similar study for a rural area in East Malaysia, obtaining a LCOE of 0.32 €/kWh for the P2P system with hydrogen storage, lower than diesel only system but still slightly higher than PV/battery solution.

In [22] Guler et al. analyse different hybrid systems combinations to meet energy demand of a hypothetical off-grid settlement of houses located in Cesme, Izmir (Turkey). Two occupancy scenarios (seasonal - 6 months and regular - 12 months) are investigated and 24 simulations are performed using HOMER software. As a result, the lowest LCOE is found for regular occupancy when diesel is used in combination with RES. It amounts to 0.26 €/kWh when hydrogen is used as storage mean, 0.17 €/kWh using battery. The authors conclude that battery storage, being a mature technology, is economically superior to hydrogen storage and the cost of energy of off-grid system is still above the cost of electricity, but less than previous years.

Another important result comes from Kalinci et al. [23]; they compare two scenarios: wind turbine and wind turbine/PV hybrid system to supply energy to a Turkish island. What comes up is that using a mixture of RES decreases the LCOE, which minimum value is 0.75 €/kWh.

An integrated modeling, simulation and optimization approach is carried out by Ghenai et al. [24] to develop a techno-economic analysis of an off-grid solar PV/fuel cell power system in a small residential community of 150 houses in United Arab Emirates. The resulting levelized cost of energy is 0.13 €/kWh.

A different load is investigated by Pietrafesa et al. in [25]. The purpose of the work is to size and optimize the chain of a stand-alone PV system aimed at satisfying the lighting needs of a university car park, generating hydrogen by electrolysis of water, subsequently stored in tanks and converted into electricity in fuel cells. The analysis has showed that, being the load active in the evening and the system disconnected from the grid, energy excess can be exploited only using large tanks or adopting high gas pressures. Consequently, the use of the system in public areas or residential buildings, where visual impact generated by large tanks or safety rules do not allow high gas pressures, is advisable only in grid connected configurations, or in stand alone ones only for small generator sizes. Such problems are by far reduced if a marked self consumption from PV is present. The assessment of COE (0.80 €/kWh) and NPC indicators confirms the current non-competitiveness of electrolytic hydrogen for energy storage, due to the still high investment cost of the system: in order to have acceptable pay back times, its cost should be reduced to about 1/4 of its current value. Also the cost of the energy unit stored in hydrogen is presently far greater than that produced by photovoltaic or wind systems or taken from the grid.

Marchenko et al. develop a research on a green power supply constituted by PV, wind turbines, battery and a system for hydrogen production, storage and energy use in the area of Baikal Lake. The analysis is not aimed to calculate LCOE, but demonstrates the efficacy of the combined use of RES and of simultaneous storage of electric energy and hydrogen [26].

The mobile telecommunication industry is an example of a sector that needs back-up and off-grid power. To supply reliable electricity for base stations where the electricity infrastructure is weak or no grid connection is available often diesel generators or diesel-battery hybrid systems are used. Each base station consumes around 10000 to 12000 litres of diesel per year [7]. Fuel cells can provide reliable power in stand-alone systems, reducing emissions in a hard to abate sector. For example, India has second largest and fastest growing telecom market, 20% of them are based on diesel generators, meaning 2 billion litres of diesel per year for towers [27].

Scarcity of works analyzing H2-based systems for off grid users in Canadian case studies have been found. Kumar et al. [28] studied hybrid energy combinations to satisfy electricity demand of an off-grid community, Sandy Lake (ON). The authors don't take in consideration hydrogen storage for the stand alone system. However, a lowest LCOE of 0.37 $/kWh is found with 21% of renewables in the energy mix shared between PV (14%) and wind (26%).

Khan et al., in a fifteen years old paper [29], developed a pre-feasibility study of a stand-alone hybrid system for St Jhon's, in Newfoundland. The most suitable solution revealed to be wind/diesel/battery system. They pointed out that a PV based system could be interesting only when wind resource is very limited and cost of diesel elevated. Moreover, the integration of fuel cells into the system was not feasible at market price of fuel cells that time. However, the authors expected that with a reduction of fuel cells cost of 35% a wind/hydrogen/diesel/battery system would have been preferable for St John's, with a LCOE of 0.45 €/kWh.

Another Canadian case study is carried on by Bhattarai et al. in [30]. The work focuses on the upgrading of the existing diesel generators set (close to the end of their operational life span) to face issue of high oversizing and the fact that they are operating well below their rated capacity. The study concludes that the integration of reduced sized diesel systems with wind energy resulted in significant reduction of cost, emissions and provides high electrical reliability.

Ely4off is an European project supported from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY whose aim is to develop a system including a PEM and a water electrolyser to be coupled with RES in off grid contexts. As a part of the project, Gracia et al. published a techno economic assessment of such hybrid system for different load configurations, finding the optimal LCOE for them [31]. After a sensitivity analysis on diesel price, they conclude recognising that diesel based system allows lower cost than any other solution in all cases dealt.

REMOTE is an EU project coordinated by Politecnico di Torino. Its objective is to demonstrate the technical and economic feasibility of P2P systems including fuel cells based H_2 energy storage solutions. Four demos in isolated micro-grids or off-grid remote areas are the objective of the work [32] [33] [34] [35]. A detailed comparison between such work and the current study is carried out in Section 5 of this thesis.

Table 1 Overview of some H_2 based P2P systems found in literature

Authors	**Year**	**Country**	**Type of load**	**Annual load (MWh)**	**COE (€/kWh)**	**Ref.**
Silva et al.	2013	Brazil	Isolated community	/	1.21	[20]
Das et al.	2017	Malaysia	Rural village	/	0.32	[21]
Guler et al.	2018	Turkey	12 detached houses settlement	60.4	0.26	[22]
Kalinci et al.	2014	Turkey	Residential district	684.4	0.75	[23]
Ghenai et al.	2018	UAE	Residential community	1642.5	0.13	[24]
Gracia et al.	2018	Europe	Isolated home	/	2.5 Tenerife 5 Edinburgh	[31]
Khan et al.	2005	Canada	Remote house	9.1	>1	[29]
Pietrafesa et al.	2019	Italy	University car park	4.8	0.80	[25]

1.4 Remote and off-grid communities across Canada

A fundamental data source for this work is Canadian Government Natural Resource website (NRCAN). At its free access address [36] a large and detailed database containing information about energy aspects of remote communities can be found. The definition of "remote community" requires a village to be neither connected to electric grid nor to natural gas grid. Such settlement must be long-term and include at least ten dwellings.

According to the most recent version of such database (2018), 338 remote communities spread across Canada, including indigenous settlements, villages, cities and non-residential outposts. This means 200000 people for whom obtaining access to affordable electricity is a constant challenge. Generally, these people rely on locally generated electricity supplied by diesel generators.

Another precious source of knowledge is represented by Pembina Institute, an experts' panel working about transition to clean energy, collaborating with industries and government leaders to face energy challenges. It provides researches, analysis and recommendations presenting perspectives on the role of energy in Canada [37]. One of the issues studied by this subject concerns indigenous and remote communities.

Innovative solutions to enable a clean energy growth economy in Canada's rural and remote communities are not lacking. For example the community of Gull Bay, located in an Indian reserve in Ontario, switched from diesel to solar power in 2019, thanks to an innovative project integrating solar PV, battery energy storage and a micro grid controller. The benefits are the reduction of 25% of diesel a year providing clean energy during the day. The 360 kW project cost 8-9 million dollars with funding from various government and private sources [38]. The community of Old Crown, in Yukon, was the protagonist of an historic signature with a local energy company [39], with the goal to install enough solar panels to offset 190000 of the 800000 litres of diesel burned per year, exploiting the sunny days in summer. The installation was completed last summer and envisages 940 kW of panels installed. The community, where the annual average temperature is -8.3 °C, relied entirely on diesel source till last year – a relevant aspect considering that there's no land road to reach the site and it is only fly-in. Fort Ware community (BC) produces part of heat and power from wood chips through a biomass to electricity process, in order to reduce reliance on diesel, decreasing greenhouse gas emissions by about 400 tonnes a year. The plant, sized 135 kW, is the first to be deployed at a remote, off-grid location [40]. Another relevant example is provided by Colville Lake community, where a hybrid solar/battery/diesel system aims to reduce the reliance on diesel and the associated greenhouse gas emissions. This case study will be analysed in depth in Section 3 of current work.

Although several initiatives to clean energy transition can be found across the Country, especially in Ontario and British Columbia provinces, large areas are still out of energy programs – also because of difficult relationship with indigenous communities. To stress the importance of the issue for the Country, Pembina Institute reported recently that in Nunavut province 31% of population live in remote areas and the most recent climate plan do not address diesel reduction targets [41].

Section 2 – Paradise River case study

2.1 Paradise River community

Paradise River is a small community placed along a rugged coastline on a tip of Newfoundland and Labrador province. Important shipping hub in the past, it was founded in 1775 by George Cartwright. Once flourishing fishmen and hunters population, Paradise River is nowadays a small scenic village frequented by indigenous people and tourists, inhabited by just a fortnight of people as a consequence of Spanish flu outbreak which decimated the population back in November 1918. The settlement is located 53°26’24” N 57°14’35” W, has a yearly round road access and rely entirely on diesel as power source. Despite climate is mitigated by sea, winters are harsh; the province records the strongest wind of Canada, especially along the coast where stations record higher winds than inland ones. Winter is decidedly windier than summer [42].

2.2 Load profile modeling

Data about electric load of remote communities are often unsure and discordant. Most of the sources report a yearly load of 189 MWh in Paradise River, corresponding to the energy request by permanent resident population of 15 people, even if other sources show higher consumptions due to temporary inhabitants moving in this community in special occasions to enjoy the natural beauty of the scenario. In this work the electrical load of just permanent population is considered.

Given the lack of data about load profile, other works have been taken as reference to obtain an adequate curve. Particularly, the estimation of load profile is based on similar studies concerning small communities elsewhere. The goodness of such assumption is verified for example in [43]: in this paper, aimed to assess the benefits deriving from use of storage for diesel-wind systems, just two categories of communities are considered (small and medium size community) to model the electric load of a typical village basing on the population. A similar approach is used in the present work since the Alaska village calculator [44] has been used as reference. This important tool allows to re-create load profile for remote and off-grid communities based on experimental data obtained in American communities (Alaska). Going in detail of the paper, this work build the load curve considering the share of load in the different sectors (residential, commercial, educational,…) and for each of them a value in MWh per person is expressed. The curve built in this way is very accurate but requires the knowledge of very detailed information, such as population, number and kind of dwellings.

The following points resume the steps and the assumptions used to adapt the Alaska village model to the present case study, starting from the annual load to get the yearly profile:

- The actual yearly load of Paradise River is broken down month by month as in Alaska village calculator, keeping the same proportions among months (example: 10% of yearly load is expended in January, 6% in August, etc.) as in fig. 4;

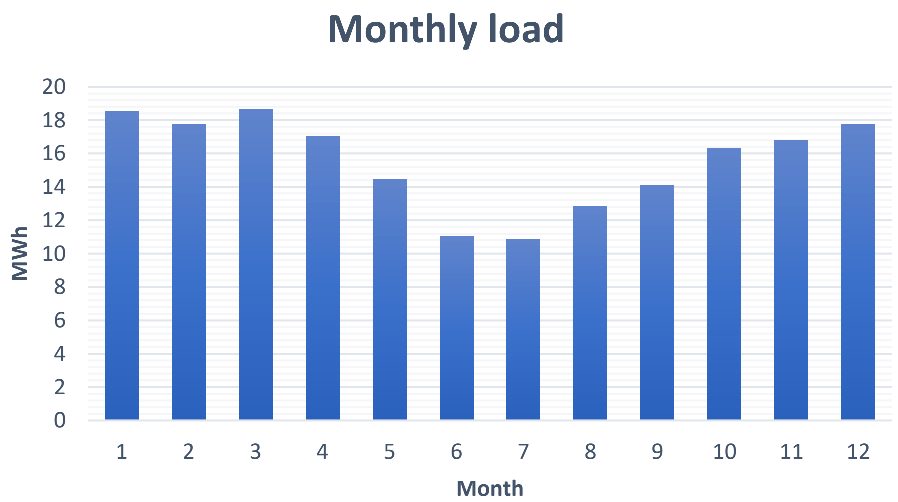


Figure 4 Energy demand over a year

- The monthly load is equally divided by the number of days of that month, obtaining daily load. In this work, in fact, the load is constant each day of each month (in other words, one day per month is considered); Example: 598.44 kWh are consumed each day in January.
- To divide the daily load hour by hour, the same share of the sample along 24 hours is considered distributing the daily load. The share is referred to the peak power

requested that day (for instance at 3:00 a.m. 58% of peak power of the day is requested, at 5:00 p.m. 96%). Examples in fig. 5;

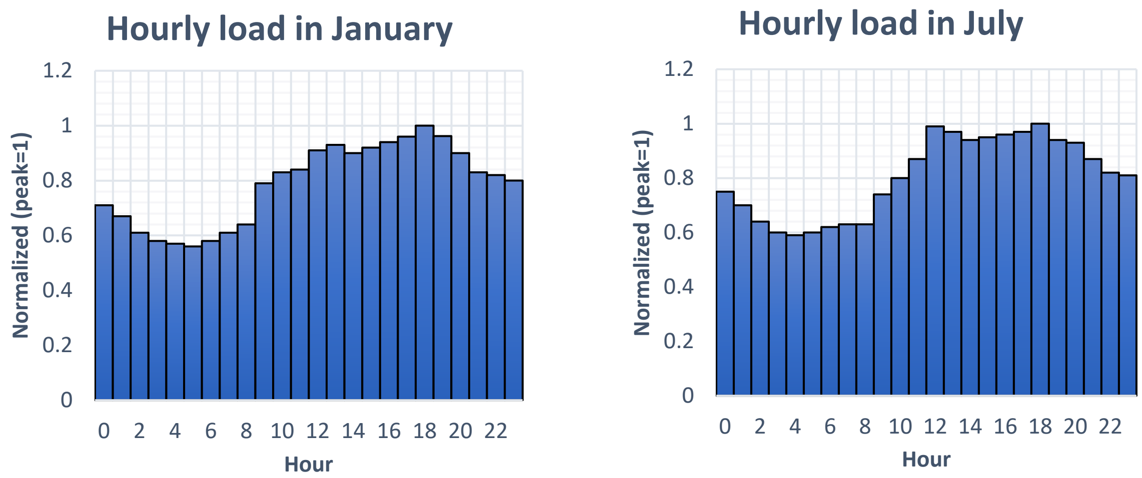


Figure 5 Energy demand over a day

- The load profile along a single day varies slightly one month from another (see fig. 6). As expected from the climate of the location, winter months load is higher

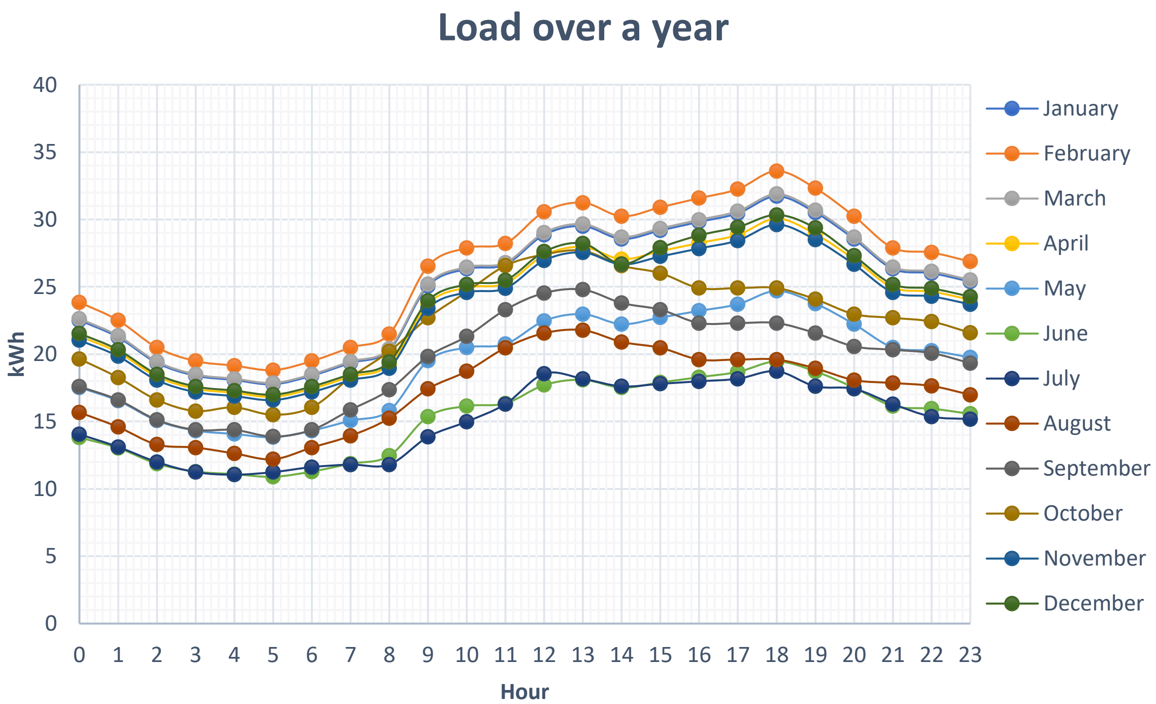


Figure 6 Daily load profile for different months

than summer one. The twelve plots like the ones in fig. 5 are adjusted consequently.

Basically, the meaning of these steps is to keep the same shape of energy load used in another similar work (for small communities) adjusting it to preserve the annual load of the present case study.

2.3 Description and preliminary sizing of the system

The following figure 7 illustrates the general scheme of the system considered as introduced in the paragraph 1.2 concerning the goal of the work:

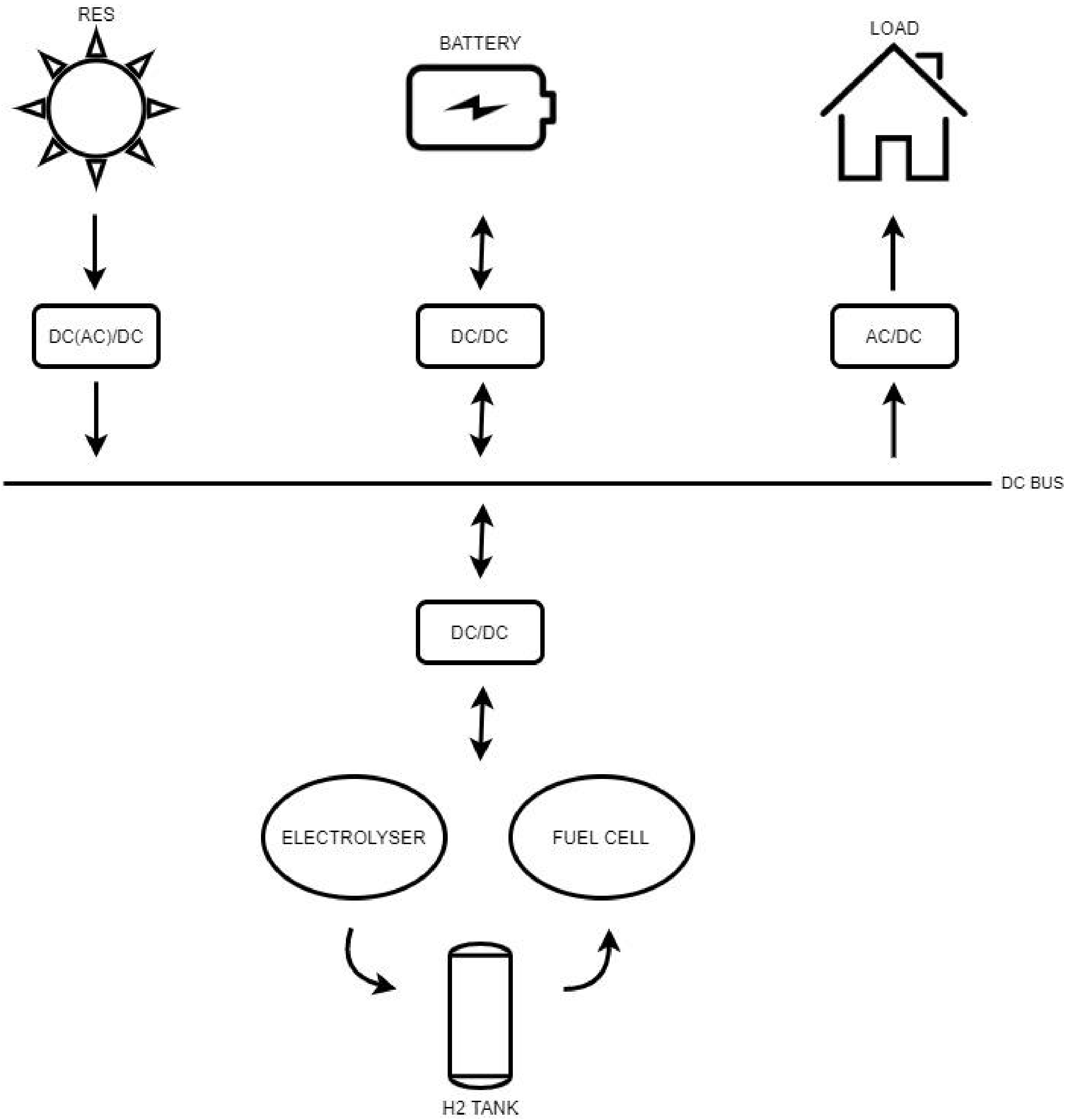


Figure 7 Scheme of the proposed P2P system

Hereafter the hypothesis assumed in the modeling:

- All the various components are electrically attached to a common DC bus. DC/DC converters are used for the connection to make the different sub-systems to exchange the correct amount of energy. In particular, since an integrated P2P system is employed, there is a single DC/DC section for the P2G and G2P devices. A DC/AC inverter is also required for the user load;
- Hydrogen is stored at low pressure (20÷30 bar), this implies no compressor is considered for storage purpose;

- PEM is the technology of fuel cell. It is fed with pure hydrogen, without requiring additional fuel supply;
- Alkaline electrolyser and lead acid batteries are taken in consideration;
- Devices efficiencies are considered constant;
- No space constraints for the tank are taken into account in this work. Of course, a more detailed study should consider this aspect too, as explained in Section 4;
- No additional loads (e.g. control, ventilation and cooling system) are considered.

The first proposed solution for Paradise River community concerns the use of solar energy as renewable source.

The general system just depicted in fig.7 has been first sized referring to [45]. This paper introduces a sizing method based on optimal energy management strategy. Considering the devices described in the paragraph, different energy flows are possible from PV to end user. The less is the number involved in energy flow, higher is the efficiency. Basically, the devices are sized to guarantee that the paths with higher efficiency are preferred (higher priority) rather than those with lower efficiency. Using the above-mentioned guidelines and the corresponding formula, the sizes of components obtained are reported in table 2:

Table 2 Sizing of the system

Component	Size
PV size	1200 m^2
Battery	1400 kWh
Electrolyser	80 kW
Fuel Cell	70 kW
Hydrogen tank	1200 kg

What first stands out is the high amount of hydrogen required. This quantity corresponds to a size tank of around 700 m^3 at 25-30 bar. A similar scenario is found in Pietrafesa et al. [25], where the results uncovers that the excess energy cannot be exploited unless large tanks or high pressure are used. This has of course consequence on visual impact and doesn't take into account special constraints and transportation issues (in hard to reach areas bring a large tank could be not feasible, see an example of logistics issues in [46]). In the present case space requirements aren't considered and the size deriving from optimization is kept in first sizing step.

2.4 RES modeling – PV

As mentioned, the first proposed solution for Paradise River community concerns the use of solar energy as renewable source. In this case, photovoltaics panels have to be installed accordingly to previous sizing method. In the following the procedure to obtain PV production along a year is described step by step. The required starting data is the irradiance (power/area) for the chosen geographical locality. PVGIS (PhotoVoltaics Geographical Information System) tool has been used, available on European commission website [47]. Once geographical coordinates of the locality, time of the year and panels angles (tilt angle, set around equal to latitude, azimuth angle, set equal to zero because north hemisphere) are put, it allows to obtain irradiance data hour by hour, one day per month, as output. A screenshot from PVGIS for solar irradiance in May is shown in figure 8.

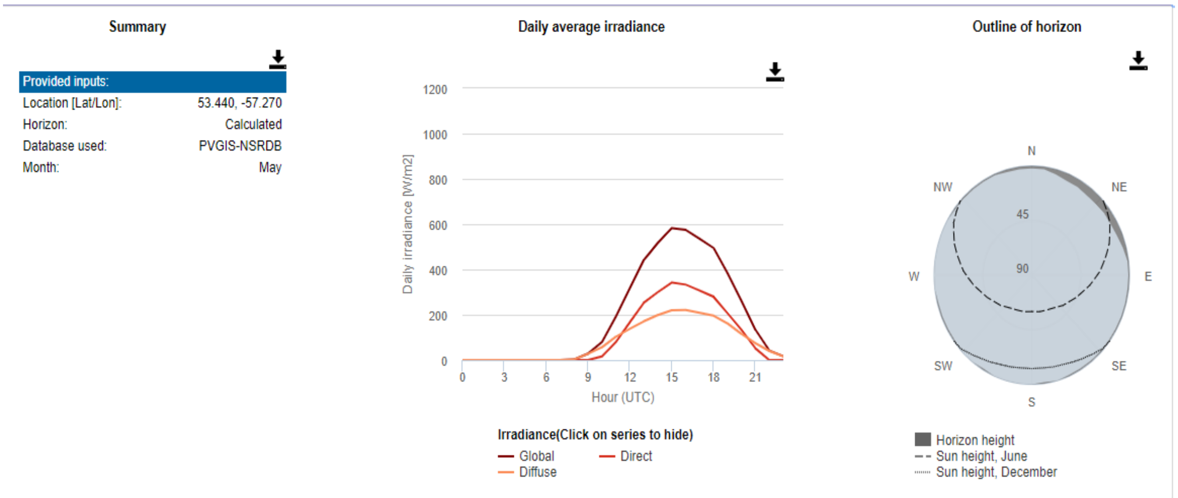


Figure 8 Solar irradiance in PVGIS software

Thus, PV production is calculated hour by hour as:

$$P\ [kW] = \frac{I\ [W/m^2] * A\ [m^2] * \eta}{1000} \tag{1}$$

Hereafter the outcomes, the data used in the calculations and the assumptions made about PV system are resumed:

Table 3 PV system data

Parameter	Value
PV area	1200 m^2
Efficiency	0.15
Tilt angle	53°
Azimuth angle	0°

Once calculated the power produced for each hour, one day per month, a PV production profile is built, in the following figure 9 the energy production month by month is shown:

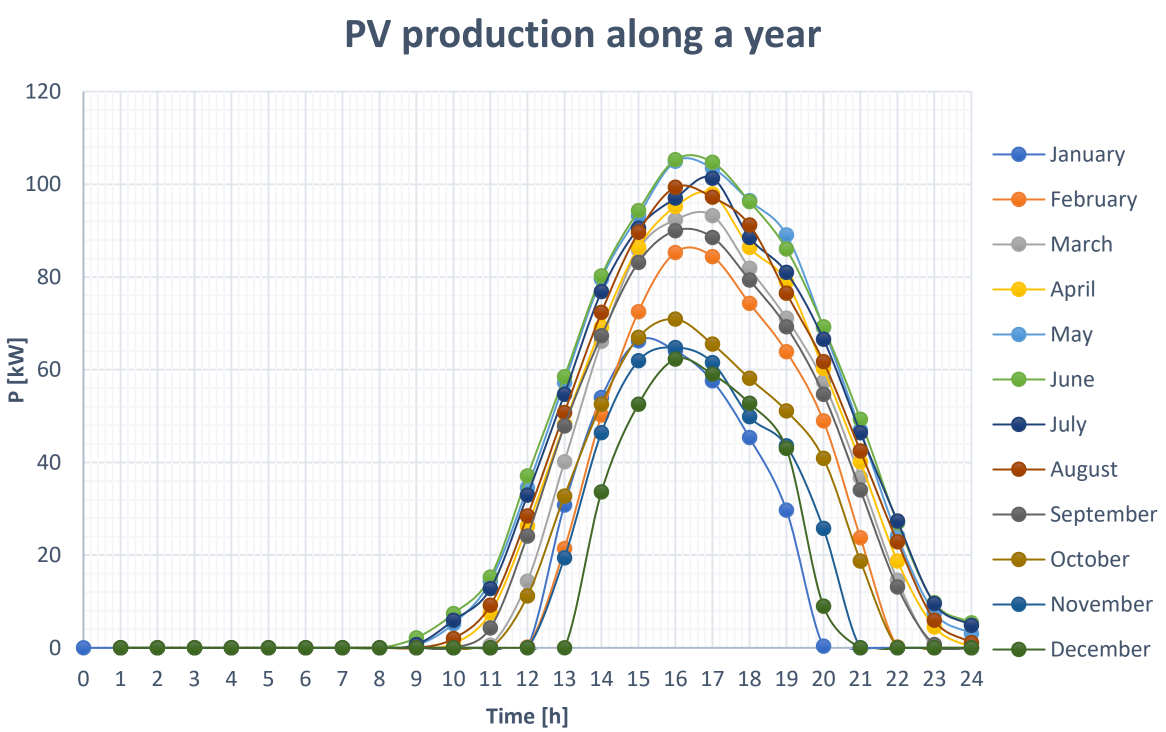


Figure 9 PV production profile

2.5 Energy balances

A Matlab script has been written to compare load and renewable production. The code gives in output the yearly energy balance, showing how much is produced and how much is consumed for each hour of the year, day by day, up to 8760 hours. Grouping by months, it's possible to compare the actual RES production with the load for each month, as in the following figure 10:

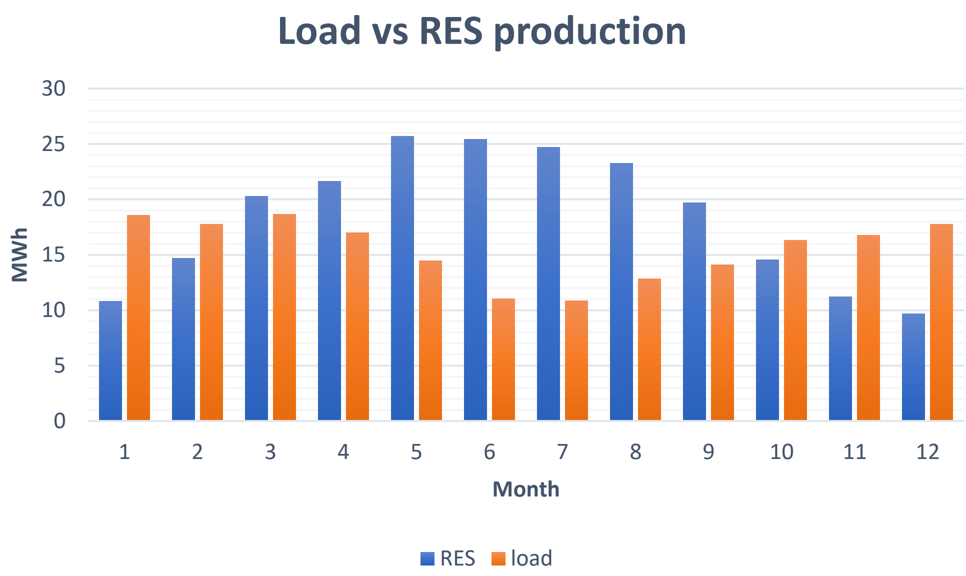


Figure 10 Comparison between load and PV production month by month

The plot highlights that in summer months RES production is high while consumption low, as is typical for cold localities. The shape of the curves suggests that a seasonal storage could make sense, since there is such displacement between histograms.

Another important outcome of this script results summing the differences between consumption and production. When production is higher than consumption, there is energy surplus, otherwise there is energy deficit. Summing these quantities for each hour of each month, the following figure 11 showing the comparison between surplus and deficit is obtained. It's important to quantify these aggregates since surplus is indicative of the possibility to store energy, while deficit means energy required.

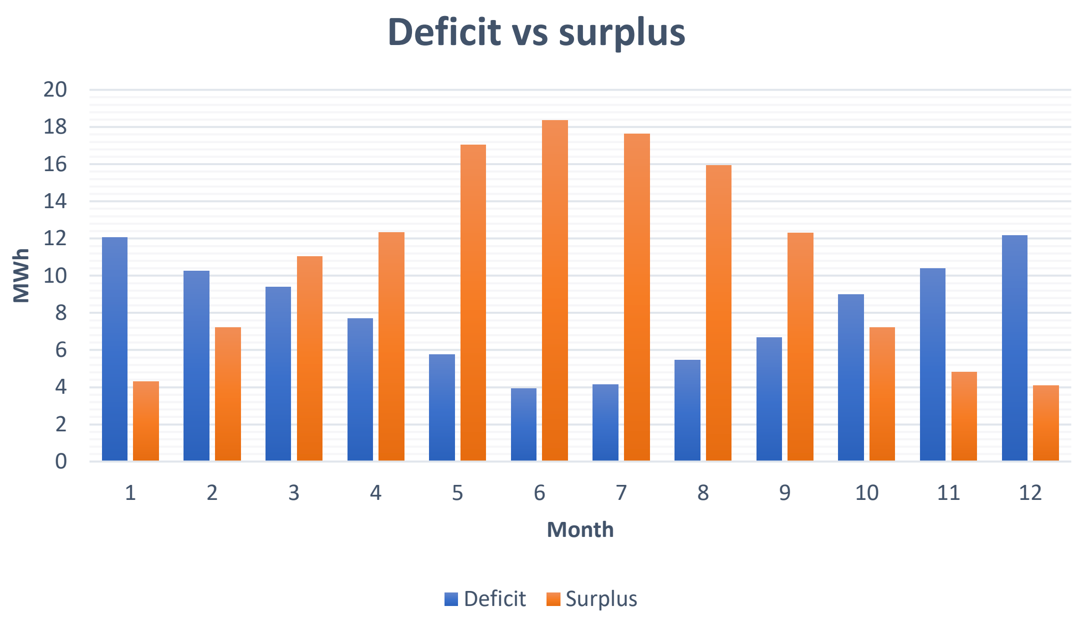


Figure 11 Energy deficit and surplus month by month

According to what has been said, surplus prevails greatly for 6 months (warmest ones) while deficit for 4 months (coldest ones). In March and October, finally, they are roughly balanced.

Next step will be to define a strategy to store energy during surplus periods and use it during deficit ones.

2.6 Energy management strategy

The aim of P2P system is to store the energy excess in form of H_2 during the surplus hours. As well, during deficit hours hydrogen stored is used to produce energy, avoiding as much as possible the use of external sources. With a hybrid storage (battery+hydrogen tank) two routes for energy storage are available. Nevertheless, thy are intrinsically different, since battery allows a short-term storage while hydrogen aims to perform a seasonal storage. The task to fulfill the energy flows among the different devices, that is the way the P2P paradigm is performed, can be assessed in different ways. In the following the three different control strategies adopted in this work are presented.

The three strategies, fitting the P2P system whose general scheme is in figure 7, lead to distinct scenarios which have been compared and investigated under the technical and economic point of view, to assess the feasibility of the system.

- Strategy 1: renewable source coupled with battery. Energy surplus from RES is stored in electrochemical form in the battery till possible (maximum state of charge, SoC). Beyond this point, it is curtailed and lost. The following flow chart depicts the logical scheme of this process, implemented through a Matlab algorithm. It represents the energy flow fate in each hour of operation.

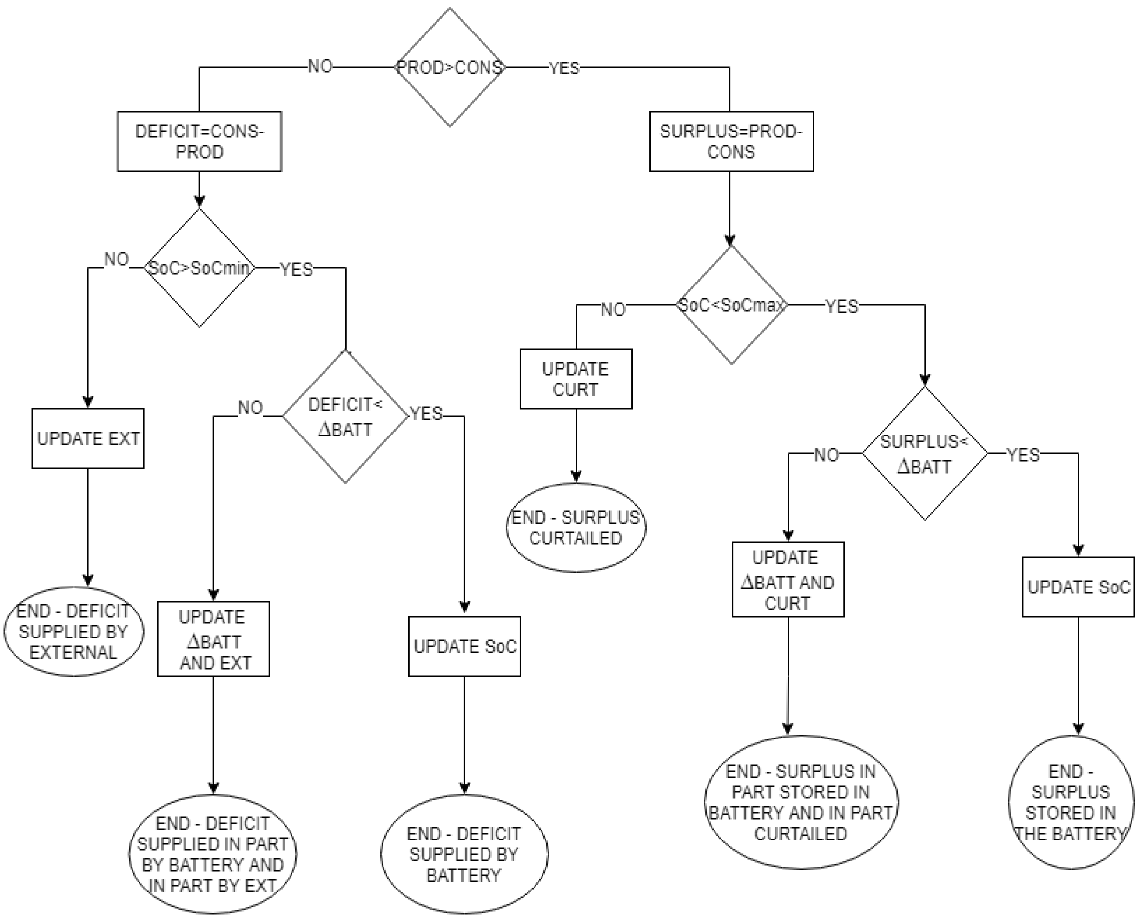


Figure 12 Logic scheme of strategy 1 (only battery as storage)
Legend – PROD energy produced, CONS energy consumed, deltaBATT energy storable in the battery, CURT energy curtailed, EXT energy supplied from external

- Strategy 2: renewable source coupled with electrolyser (alkaline) and fuel cell (PEM) in order to have hydrogen as chemical storage exploiting the energy surplus and use it in case of deficit. When the energy available is too much compared to electrolyser size, it is curtailed. The same happens when the hydrogen tank is full. When there isn't enough hydrogen to be converted in electricity to cover the load, an external source will be necessary. Hereafter the logical scheme:

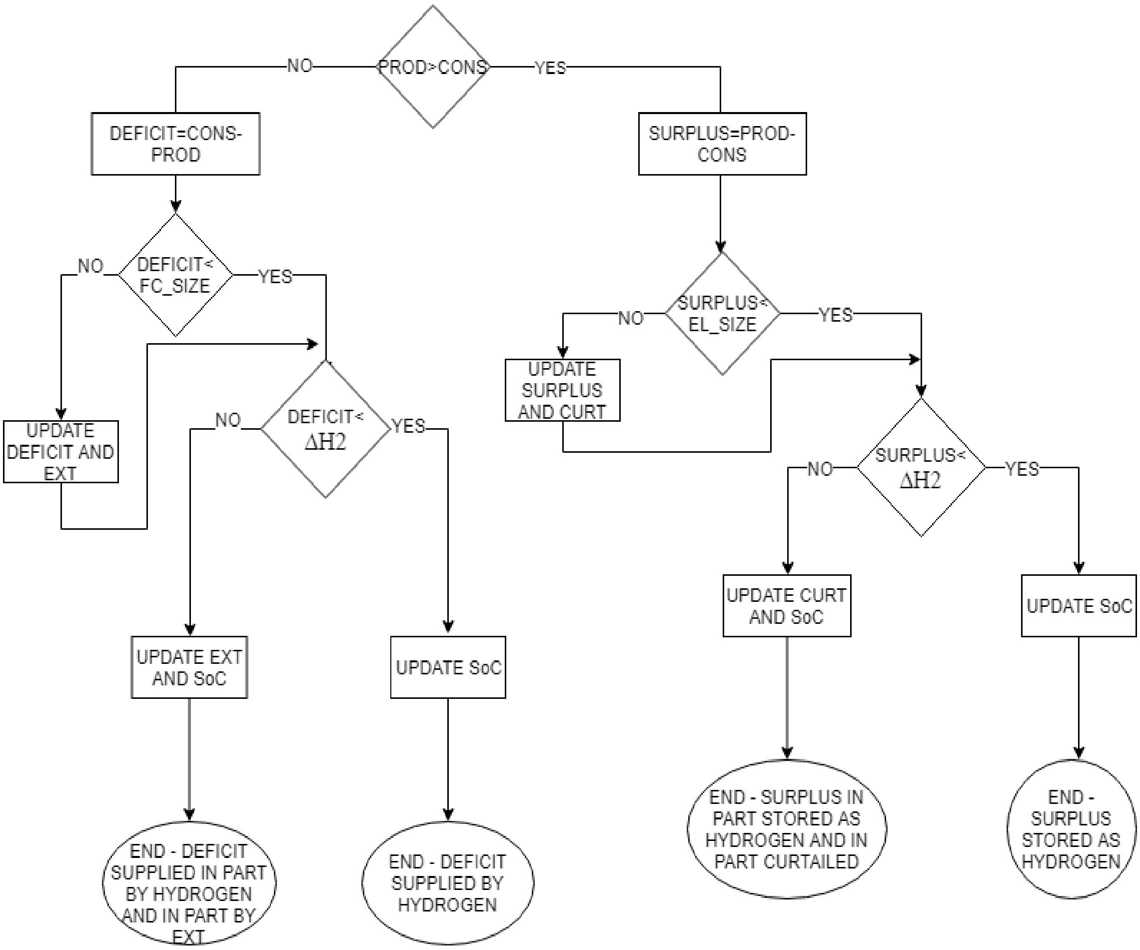


Figure 13 Logic scheme of strategy 2 (only hydrogen tank as storage)
Legend – deltaH2 energy storable in the hydrogen tank, SoC state of charge of hydrogen storage

- Strategy 3: RES coupled with battery, electrolyser and fuel cell (complete P2P system). The energy surplus is stored first in the battery, then as hydrogen produced by electrolyser. When no storage is available, energy curtailment takes place. When energy is required (deficit phase) first the battery, then hydrogen tank are discharged (producing energy through the fuel cell in the latter case). Neither fuel cell charges the battery nor battery feeds the electrolyser in this work.

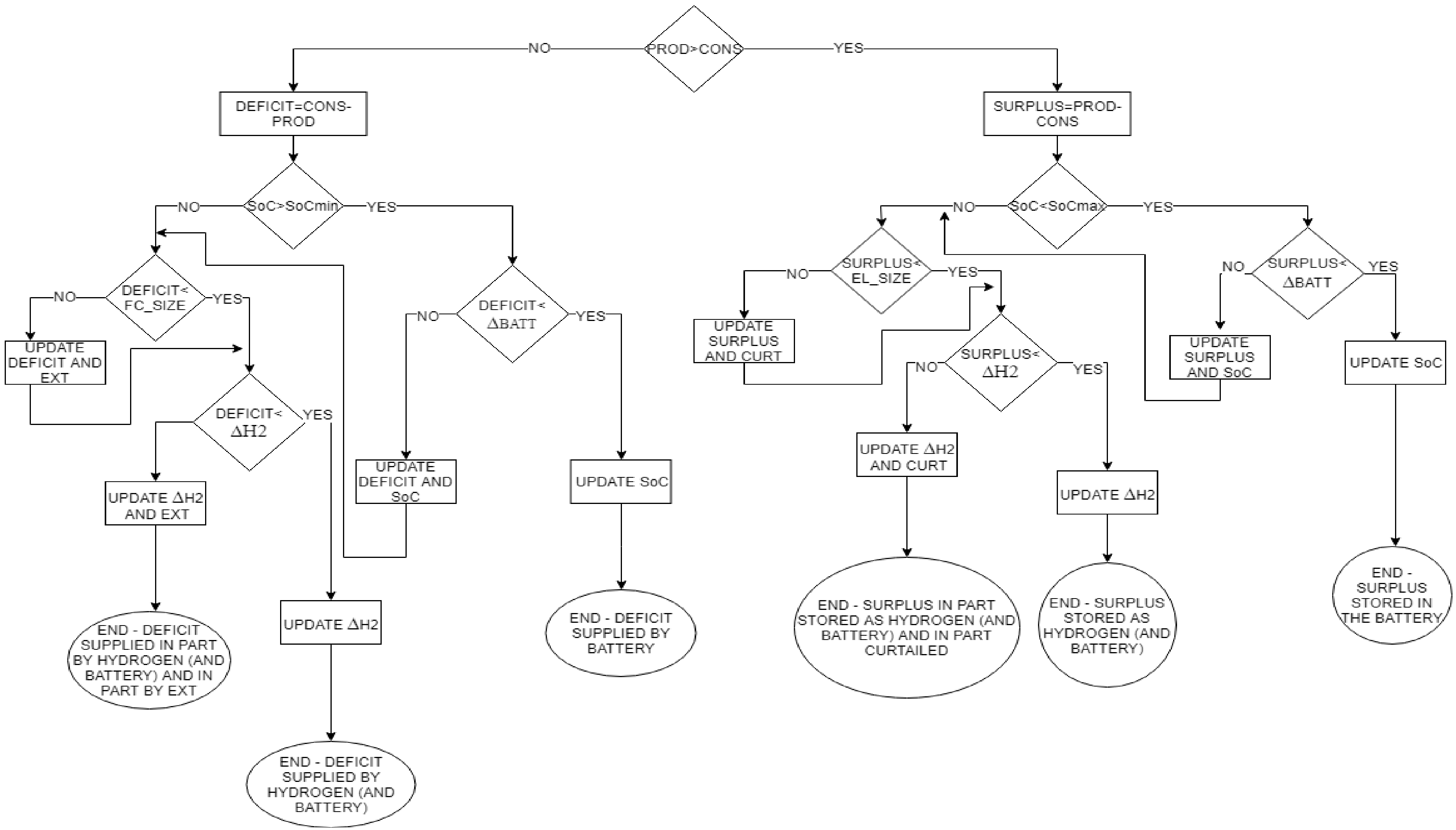


Figure 14 Logic scheme of strategy 3 (battery and hydrogen tank as storage)
Legend –SoC state of charge of battery, deltaH2 energy storable in the hydrogen tank,

The technical hypothesis used for the simulation are resumed in table 4. They are typical values chosen according to current technology and consistent with other studies of this kind [22], [31].

Table 4 Hypotesis for simulation

Parameter	**Description**	**Value**
SoC min battery	Battery minimum state of charge	0.2
SoC max battery	Battery maximum state of charge	0.9
η battery	Battery efficiency	0.9
η el	Electrolyser efficiency	0.85
η fc	Fuel cell efficiency	0.55
FC size	Fuel cell nominal size	70 kW
EL size	Electrolyser nominal size	80 kW

2.7 Simulation

The three strategies described above have been implemented for Paradise River adopting the data of load and RES production obtained in the previous paragraphs. The goal of this part is to see how the RES production is used and how the load is covered, in other words to understand which the destinations of each MWh produced are and which the sources of each MWh required.

Simulations have been achieved running Matlab codes implementing control strategies (see previous paragraph) and elaborating the results on Excel, in order to have adequate tables and plots. The next pictures (figure 15) refer to the application of strategy 3, leading to an energy configuration named scenario 3. The table on the left is about the usage of renewable source, while the one on the right concerns the load coverage. The same data are reported month by month in the plots.

TOT RES (MWh)	221.676
% LOAD	40%
% BATTERY	36%
% ELECTROLIZER	21%
% CURT	3%

TOT Load (MWh)	186.362
% RES	48%
% BATTERY	35%
% FC	9%
% EXT	7%

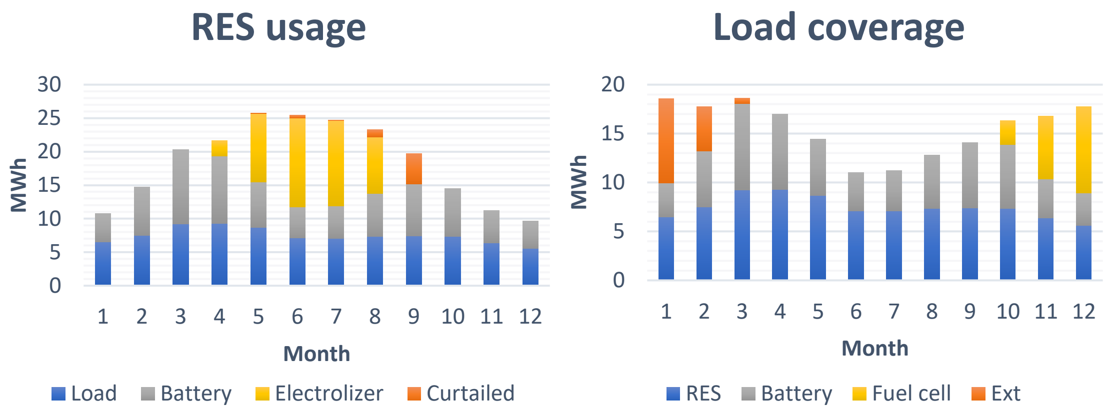


Figure 15 RES usage and load coverage for scenario 3
Legend: CURT: energy curtailed; FC: energy provided by fuel cell; EXT: energy provided from external (diesel generator)

This configuration leads to a good exploitation of the renewable source, as confirm just 3% of energy curtailed. The battery is charged mostly during winter months while the electrolyser receives energy during summer. Energy curtailment occurs mostly in September, when the RES production is still quite high but the energy tank is full. Concerning the load coverage, during the last months of the year the hydrogen feed the fuel cell to produce electricity required by the load, while most of the energy from external (7% of the load) is required during the first months of the year, when the load is high and hydrogen tank empty. The following figure 16 shows the state of charge of hydrogen tank along the year:

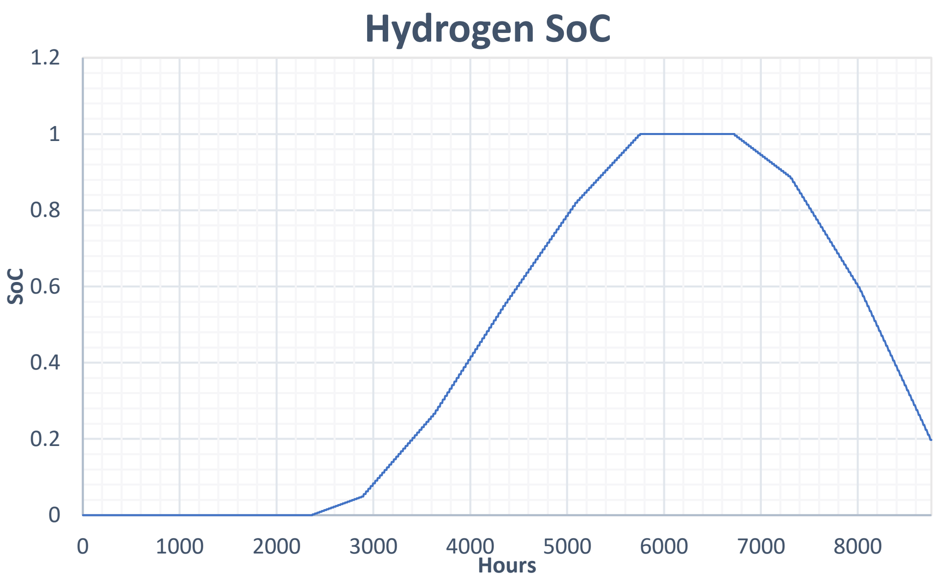


Figure 16 Hydrogen tank SoC along a year

This profile suggests a suitable seasonal storage management, since the tank is full during the hottest hours of the year and empty for around 3 months at the start of the year. The charging phase occurs at increasing slope steps, since spring months are gradually warmer. Analogous it happens for discharging phase, whereas the slope is stronger due to colder months quick approach.

Now strategy 2 is considered. It is expected that, without battery, a larger part of energy will be required from external. At the same time, electrolyzer and fuel cell usage is expected to increase, since they will be more stressed. Once ran the simulation and elaborated data, the plot showing H_2 SoC is first showed.

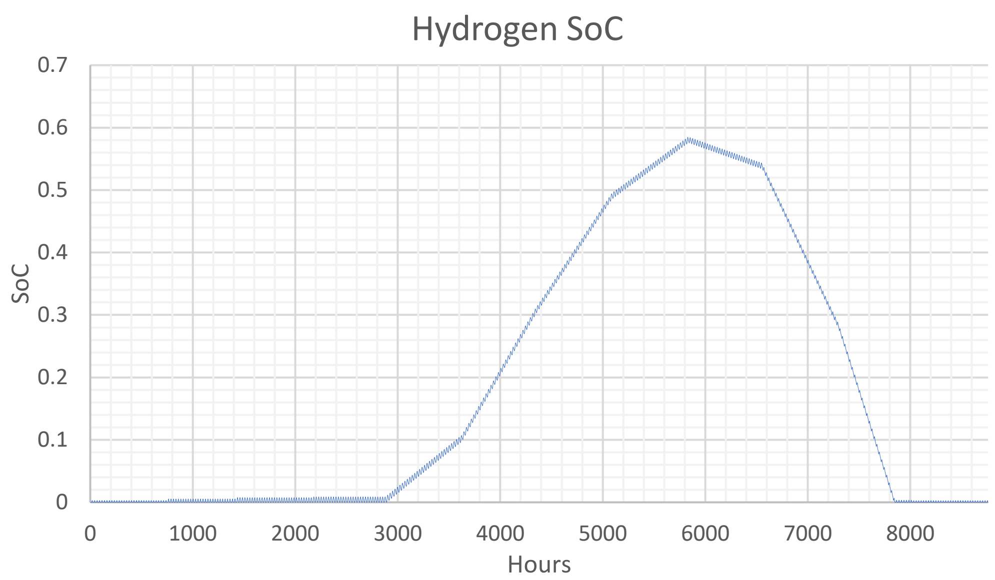


Figure 17 Hydrogen SoC for strategy 2

It is noticed that, differently from previous scenario 3, hydrogen tank is never full. SoC reach almost 60% for a few hours, and for large part of the year it is below 50%. This is indication that the tank is oversized. To avoid this, different attempts have been made to improve the tank size and find an adequate value. The comparison is shown in figure 18.

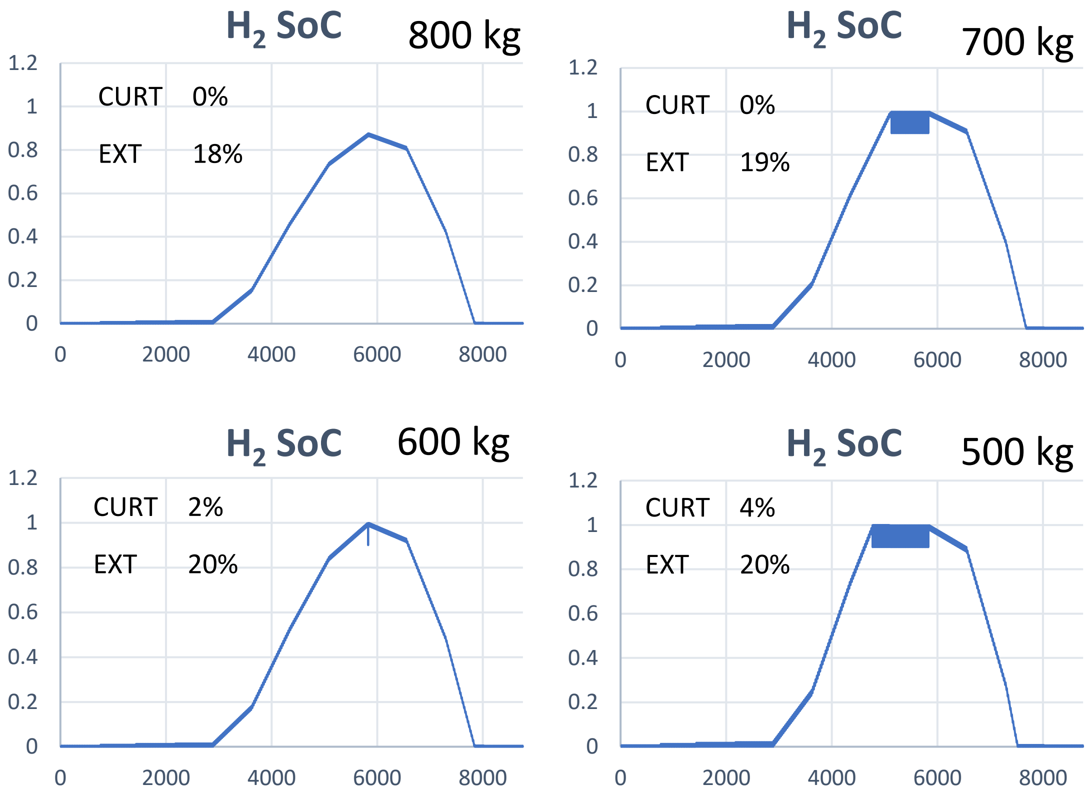


Figure 18 SoC comparison among different hydrogen tank size

Comparing the above plots, a tank of 700 kg seems to be the most reasonable choice, since it leads to SoC=1 for a number of hours in the summer, and to keep low energy curtailed as well. The trends are justified noting that reducing tank size means having less storage available (higher curtailment), even if the SoC is larger on average. On the other hand, very large storage decreases curtailment but implies worse tank fulfilling, that is worse SoC values. Such tank size change is necessary because optimization guidelines used previously refers only to complete P2P system (with battery also). The heuristic optimization adopted aims to keep in consideration both the SoC and the minimization of curtailment and external requirements. To simulate energy performances, such tank will be used for this strategy implementation (scenario 2). Here, in fig. 19, the technical outcomes of the simulation are shown:

TOT RES (MWh)	221.676
% LOAD	40%
% ELECTROLIZER	59%
% CURT	0%

TOT Load (MWh)	186.362
% RES	48%
% FUEL CELL	33%
% EXT	19%

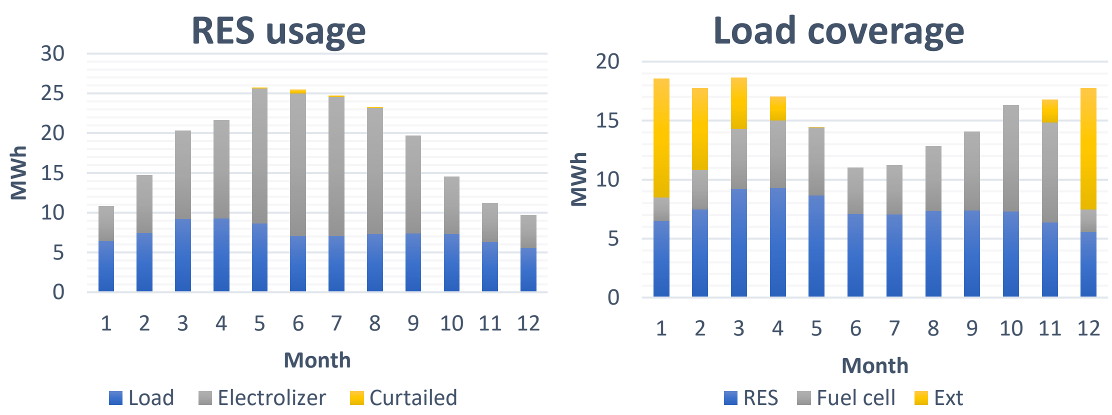


Figure 19 RES usage and load coverage for scenario 2

In this case the RES usage is improved because less energy is curtailed (just 678 kWh) due to the absence of the battery, but the external requirement increases and occurs also at the end of the year, when in scenario 3 hydrogen was enough to cover that load.

Finally, strategy 1 is considered. In figure 20 the technical outcomes of this configuration (scenario 1) are illustrated:

TOT RES (MWh)	221.676
% LOAD	40%
% BATTERY	36%
% CURT	24%

TOT Load (MWh)	186.362
% RES	48%
% BATTERY	35%
% EXT	17%

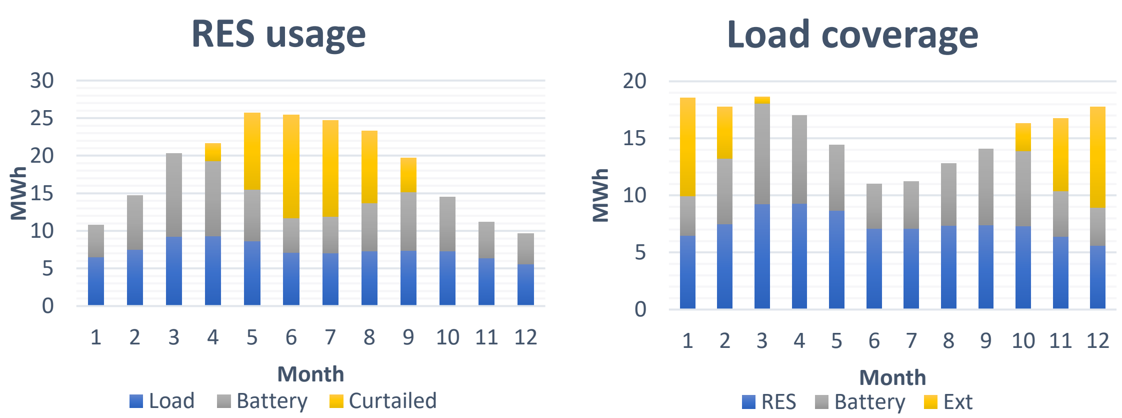


Figure 20 RES usage and load coverage for scenario 1

This last case envisages a significant increment in the energy curtailed and high requirement from external, similar to scenario 2. As the plots show, in fact, the battery is not large enough to store the high summer surplus and to cover the peak of load in winter months.

Overall, the two cases with a single storage lead to comparable high values of external energy requirement, while concerning curtailment using H_2 turns out to be eventually better with the current sizing, since it can store much more energy (lower energy curtailed).

2.8 RES modeling - wind energy

Once investigated the use of solar panels to produce energy, in this chapter the use of wind energy is inquired. Previous studies show wind energy to be much promising for north Canada [48], moreover the geographical position of the locality suggests a positive feedback from wind resource.

To assess wind energy production, it is necessary to have adequate data on wind speed. In this work the source is Canada Wind Atlas [49], which reports accurate data about meteorologic conditions with high space and time resolution. Data have been elaborated in order to have a set similar to the one used for solar energy. Specifically, one day per month has been chosen, one value for each hour (time resolution provided is 10 minutes). In figure 21 these data are reported for years 2010, 2009, 2008, the most recent ones available.

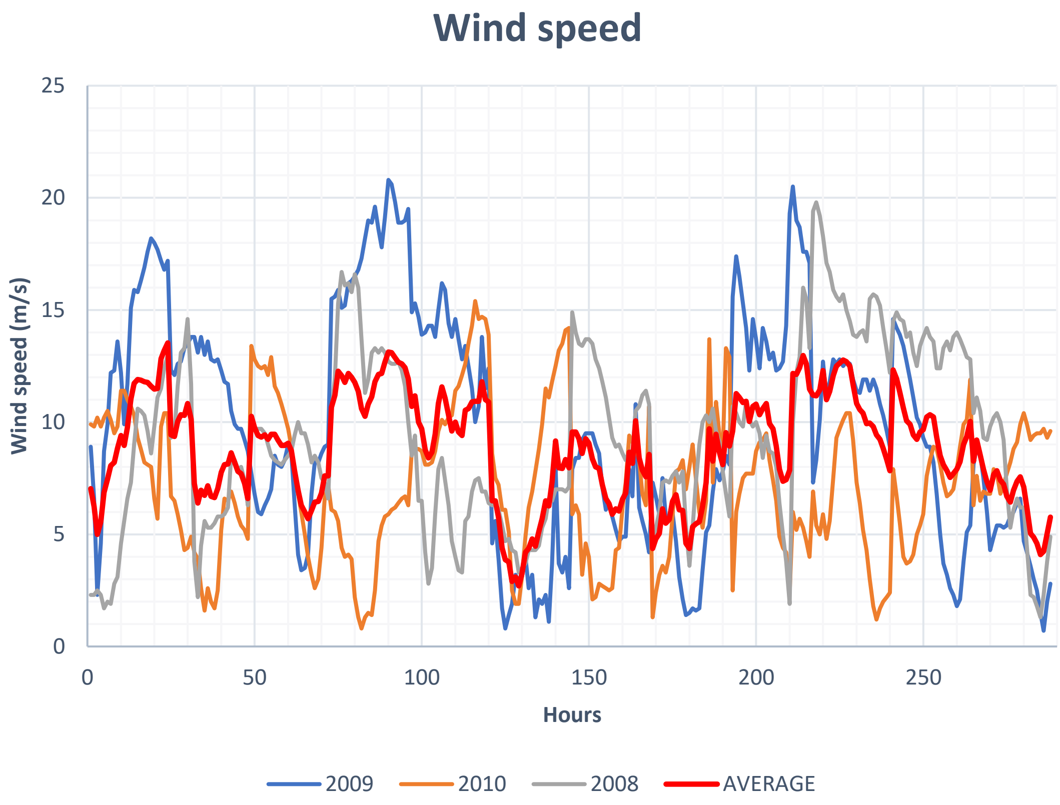


Figure 21 Wind speed in different years and average

A great variability can be seen from one year to another. For this reason, the average value among the three years has been computed and it is reported in the same figure, red curve. Broadly speaking, the months of May and June result to be few windy, while fall months turn out to be very windy.

Moving from wind speed to wind energy production means to have the relationship between wind and power produced by the wind turbine. In this case a real model of turbine has been considered. The choice is 10 kW Bergey Excel 10, which power curve is shown below [50].

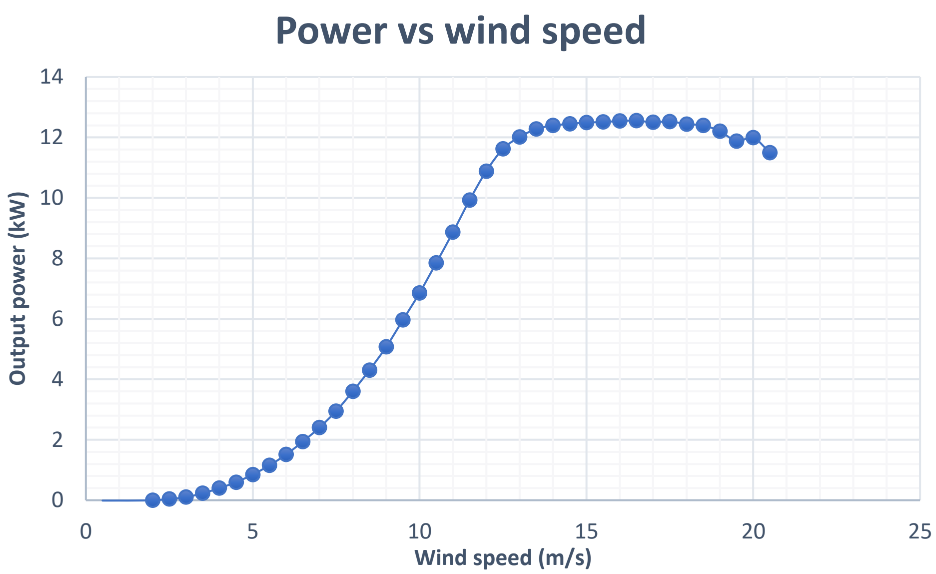


Figure 22 Power curve of a Bergey Excel 10

The choice of this model of turbine is strengthened by other studies [31], [51] since it has been in the market place for over 30 years and has been used the world over.

The criterion to choose the size of wind farm is same yearly energy produced than PV. This means that the same three strategies will be analyzed using a wind farm producing an amount of energy equal to the one produced by the solar system over a year. As next paragraphs will show, a wind farm of 5 turbines (50 kW of wind energy) produces roughly the same yearly energy of the PV system already discussed before.

2.9 Balances and simulation

Using the power curves discussed in the previous paragraph, the RES production has been estimated associating the actual wind speed over time to power produced. It is then compared to the load in figure 23 and figure 24, where deficit and surplus are made explicit.

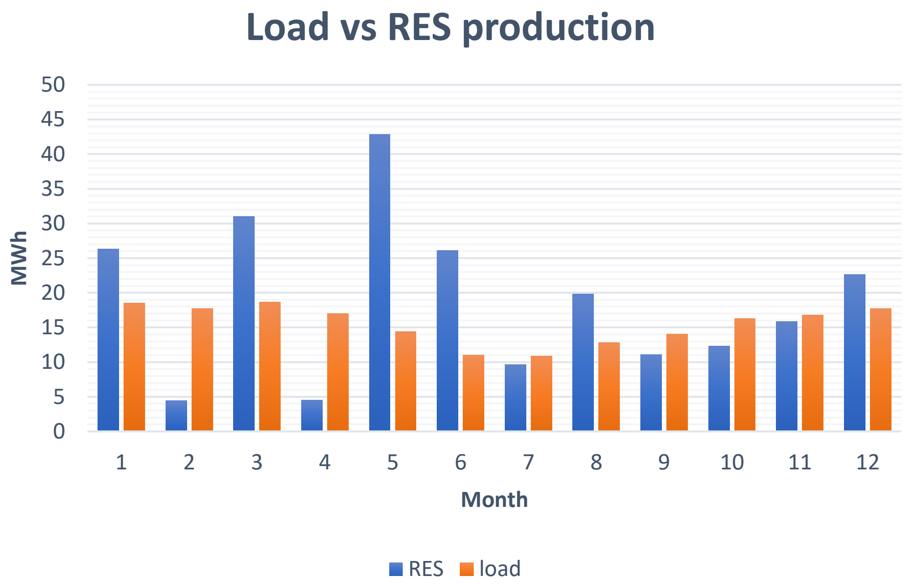


Figure 23 Comparison between load and PV production month by month

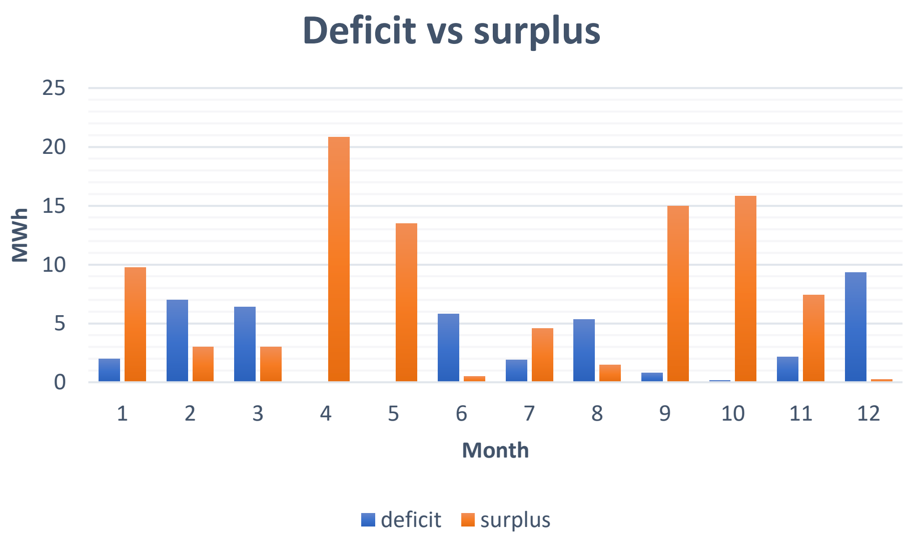


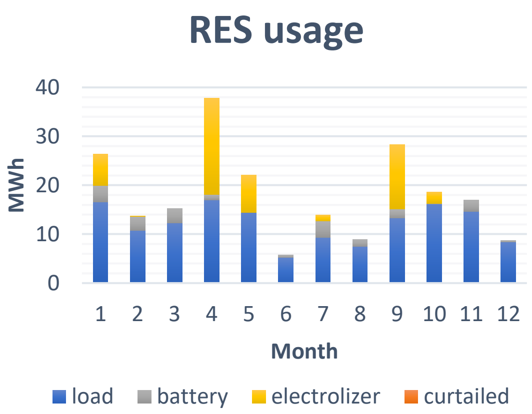
Figure 24 Energy deficit and surplus month by month

Comparing these plots with the corresponding for solar energy (fig. 10 and 11), it's clear how wind energy is much more variable and intermittent than PV. In the second plot it is noticed that in some months (April May, September, October) very high energy surplus occurs, while in December and June almost only deficit takes place.

Keeping constant other devices sizes, the three scenarios corresponding to the three control strategies described previously have been simulated. The following figure 25 summarises the outcomes referred to strategy 3:

TOT RES	240.748
% LOAD	62%
% BATTERY	9%
% ELECTROLIZER	30%
% CURT	1%

TOT Load (MWh)	186.362
% RES	78%
% BATTERY	9%
% FC	10%
% EXT	3%



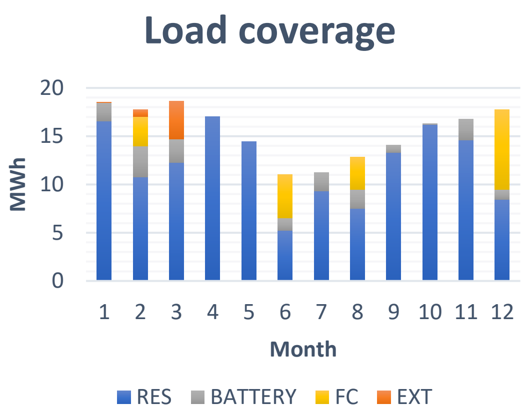


Figura 25 RES (wind) usage and load coverage for scenario 3

Looking at the tables the general prospectus is better than the same strategy with PV as RES (fig. 15), since curtailment and external need are lowered. Observing the diagrams, less homogeneity is noted than PV case. The use of electrolyser and fuel cell is now spread along the year, while the months when an external source is necessary are still the first three of the year. The state of charge of hydrogen tank is showed in figure 26.

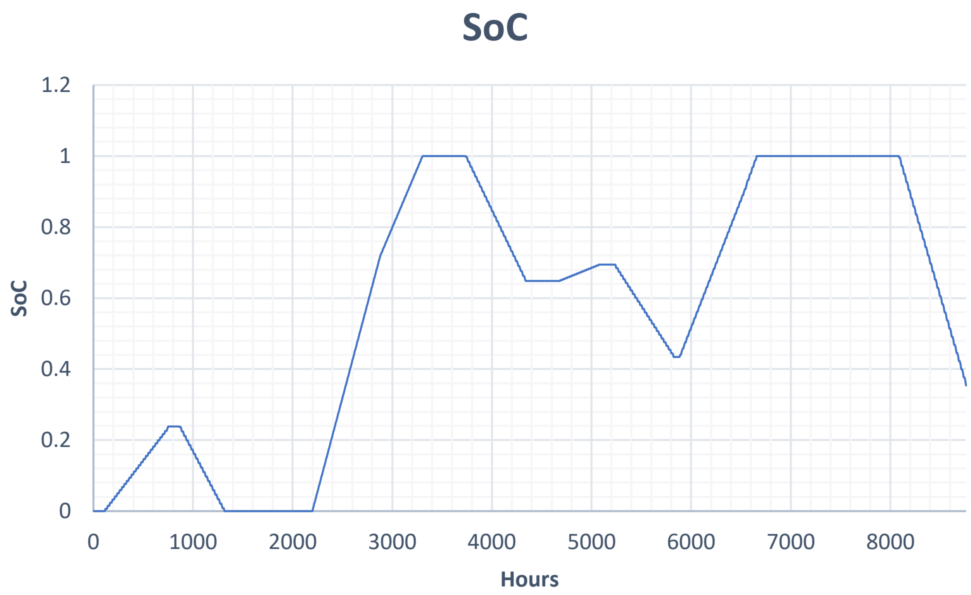


Figure 26 State of charge of hydrogen tank

Moving to strategy 2, a similar consideration than PV case can be done. Using the tank size deriving from initial optimization, in fact, the storage turns out to be oversized. Several attempts have been done to find out the best choice:

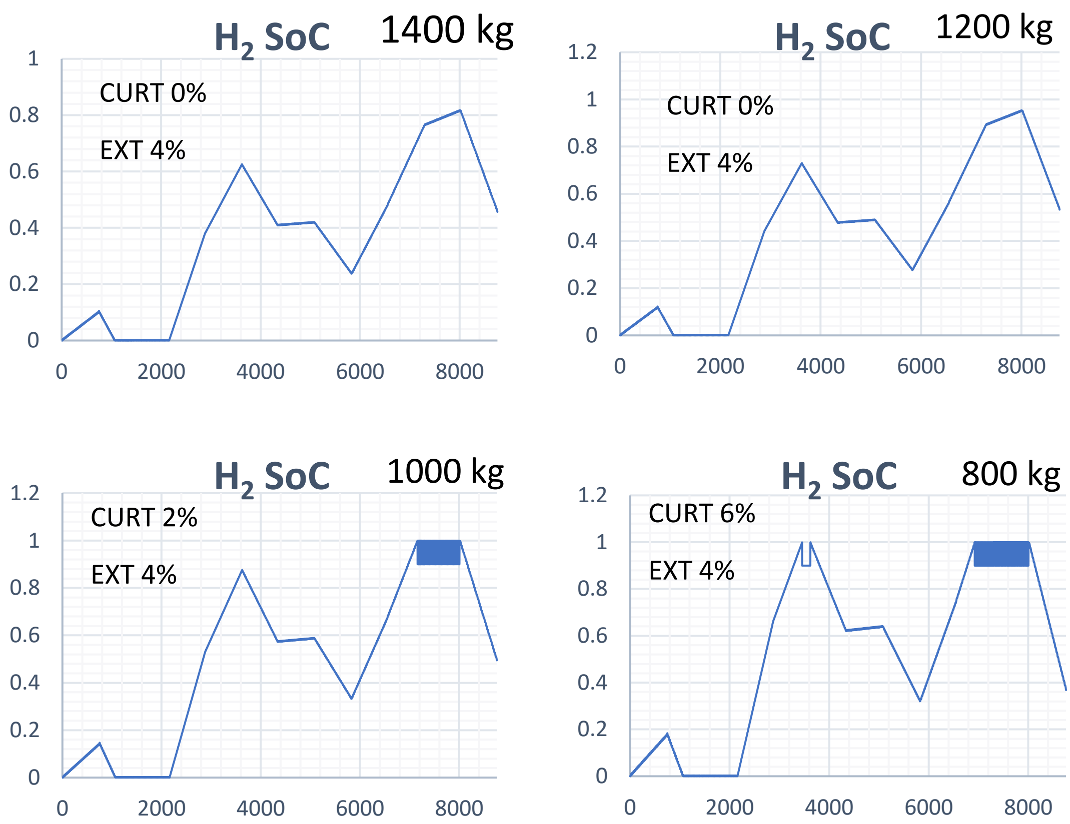


Figure 27 SoC comparison among different hydrogen tank sizes

Following the sensitivity analysis, a 1000 kg H_2 storage turns out be the best choice, representing a trade off between good SoC along the year and minimum energy curtailed. Decreasing the size, in fact, the usage of the tank enhances (fuller along the year) but the energy curtailed increases as a consequence of the lack of further storage opportunity. The external needing remains the same in the four cases showed, this means that it occurs when the tank is void.

The simulation implementing strategy 2 leads to these outcomes:

TOT RES (MWh)	240.748
% LOAD	60%
% ELECTROLIZER	37%
% CURT	2%

TOT Load (MWh)	186.362
% RES	78%
% FUEL CELL	18%
% EXT	4%

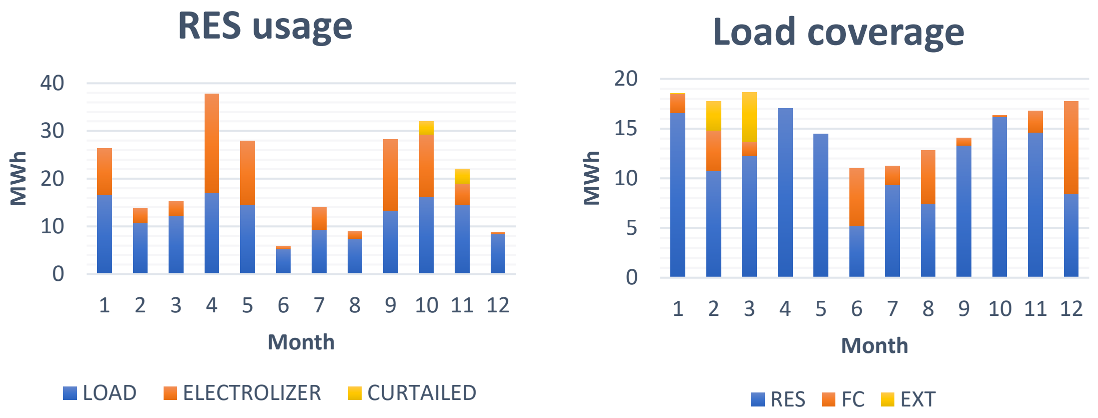


Figure 28 RES (wind) usage and load coverage for scenario 2

Moving from the case with battery to the one without, the energy curtailed increases from 0% to 2%, while the external needing increases slightly as well (from 3% to 4%). The high winter load must be covered by external source in February and March, when H_2 storage empties.

Finally, hereafter the results of simulation of scenario 1:

TOT RES (MWh)	240.748
% LOAD	60%
% BATTERY	8%
% CURT	31%

TOT Load (MWh)	186.362
% RES	78%
% BATTERY	9%
% EXT	13%

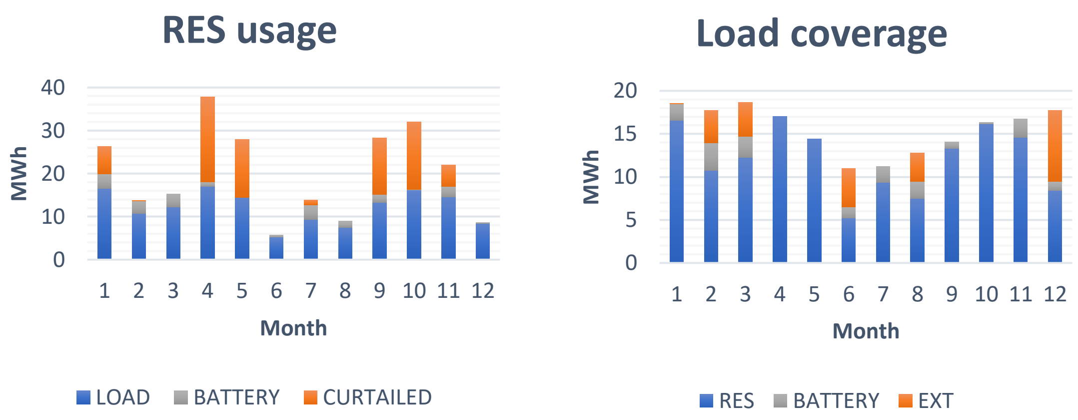


Figure 29 RES (wind) usage and load coverage for scenario 1

While scenario 2 shows rates and trends in conformity with strategy 3, strategy 1 displays a significant worsening in the energy balances, with energy curtailment in almost all the year and external need in 5 months. High curtailment takes place in most windy months, when the load is covered fully by RES. For instance, there is no way to store the high surplus in April and May, when the load is low and the battery full.

Even carrying general better technical performance, the employment of wind as RES results in very high curtailment when battery is the only storage option (scenario 1), while ensures lower external requirements for all configurations.

The results shown so far reflect technical performances and have to be validated through the economic analysis of next paragraph.

2.10 Economic analysis

The technical analysis is not exhaustive to assess the feasibility of a system and cannot be the only criterion in decision making among different alternatves. The economic analysis carried out in this chapter aims to calculate the Levelized Cost of Energy (LCOE) for the different scenarios, in order to find the best option in techno-economic terms. LCOE allows to estimate the average cost of generating electricity (€/kWh) when all life-cycle costs are taken into consideration. Essentially, it is a modified cash flow analysis including capital costs, lifetime operation and maintenance costs, fuel costs and decommissioning costs. This net present value is then divided by the total amount of energy expected to be generated over the life of the system. Such analysis produces a simple unit cost, so it is easy to compare results across different energy alternatives.

Mathematically, LCOE is calculated through the following formula [45]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2}$$

Where the meaning of the quantities is:

I_t: investment expenditures in year t;

M_t: operations and maintenance expenditures in year t;

F_t: fuel expenditures in year t;

E_t: energy produced in year t;

r: discount rate;

n: life of the system.

The summation index (t) represents the time going from year 1 to lifetime n.

Thus, other than the energy produced, it is necessary to calculate the costs of the system during the lifetime. In this work for each component capital costs (capex), operative costs (opex), and replacement costs have been considered (numerator in (2)). Fuel expenditures are not considered since renewable systems are investigated. Recurring costs (opex) are calculated as a percentage of capital cost or as a fixed rate (see next paragraph) and don't take in consideration distinction between maintenance and operation costs. Moreover, a trend costs has been drawn for each scenario. Since it requires the calculation of cash flows in different years, net present costs are needed as well as interest rate. LCOE thus calculated is used as a decision-making criterion among different scenarios[3].

2.10.1 Cost breakdown

The following table 5 summarises the hypothesis adopted in this work for the economic analysis, accompanied of references. Sometimes large discrepancy has been detected among different sources, since costs depend on many factors. In those cases, the most reasonable choice has been done by the author, also trying to be consistent with the data of REMOTE project, object of a comparison in Section 5.

[3] Further considerations on the limit of this choice are discussed in conclusions, Section 5.

Table 5 Economic analysis assumptions

	capex	opex	replacement	lifetime	references
PV panels	1670 €/kWp	1330 €/kWp	3% of capex	20 years	[45]
Lead acid batteries	175 €/kWh			10 years	[52]
Electrolyser	1200 €/kWh	3% of capex	1200 €/kWh	20 years	[45][45]
Fuel cell	5 €/W	3% of capex	5 €/W	5 years	[22]
Hydrogen tank	180 €/kg	3% of capex	180 €/kg	20 years	[31][51]
Wind turbine	45000 €/turbine	2.5% of capex	75% of capex	20 years	[22][31]
Diesel generator	420 €/kW	0.4 €/h + 2€/l	420 €/kW	2 years	[53]

Diesel price

It's a well-known issue that high price of fuel in remote communities is a main concern, as well as one of the driving reasons toward alternative solutions to diesel generators use. High price is usually due to problematic fuel transportation, because of distances and difficulties to reach some areas. The price adopted for Paradise River case study is the same of Cartwrigth, a city far 30 miles from reasonably the fuel come from by land road. Web news report constantly that in NL region the highest price is recorded in Labrador South-Lodge Bay/Cartwright [53], where Paradise River is located. The most recent price found is dated January 2019, and it is 1.29 CAD/l. This benchmark value has been used for the economic analysis.

The lifetime of the whole system, that is the time over which the economic analysis has been led, is assumed to be 30 years. This choice is also consonant on what done in REMOTE project. The interest rate has been set equal to 1.75% (data of June 2019) [54].

2.10.2 Steps of economic analysis

Once individuated total cost for each component, a table has been built for each scenario (examples in figures 30, 31, 32). In such table costs trend are reported and then plotted on a diagram (like the on in figure 33). Over the period of 30 years, year by year, total costs have been computed summing capex, opex and replacement cost of components in the system. The net present cost has also been computed, according to the formula:

$$NPV = \frac{Cash\ flow_t}{(1+r)^t} \tag{3}$$

Where $Cash\ flow_t$ is the net total cost (algebraic sum) comprehensive of all incomes and outcomes in year t.

The sixth column reports the cumulative of the present costs and represents the y axis of the diagram (fig. 33). Finally, the unit cost has been computed as:

$$Unit\ cost_t = \frac{Net\ costs\ after\ t\ years}{Energy\ produced\ after\ t\ years} \tag{4}$$

2.10.3 PV case results

In this part outcomes from the economic study are shown. The column ‘suggested solution’ refers to scenarios 3,2,1 previously presented (fig. 30, 31, 32 respectively), while ‘current solution’ refers to diesel-only situation, that is current status.

	SUGGESTED SOLUTION							CURRENT SOLUTION					
year	capex (€)	opex (€)	replacement (€)	tot cost	present costs	cumulative	Unit costs	opex (€)	replacemer	tot costs	present cost	cumulative	Unit costs
0	1,207,600.00 €			1,207,600.00 €	1,207,600.00 €	1,207,600.00 €				0.00 €	0.00 €	0.00 €	
1		32,681.74 €		32,681.74 €	32,119.65 €	1,239,719.65 €	6,665.16 €	73,785.20 €		73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		32,681.74 €		32,681.74 €	31,567.22 €	1,271,286.86 €	3,417.44 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		32,681.74 €		32,681.74 €	31,024.29 €	1,302,311.16 €	2,333.89 €	73,785.20 €		73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		32,681.74 €		32,681.74 €	30,490.71 €	1,332,801.87 €	1,791.40 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		32,681.74 €	350,000.00 €	382,681.74 €	350,885.68 €	1,683,687.55 €	1,810.42 €	73,785.20 €		73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		32,681.74 €		32,681.74 €	29,450.91 €	1,713,138.46 €	1,535.07 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		32,681.74 €		32,681.74 €	28,944.38 €	1,742,082.83 €	1,338.01 €	73,785.20 €		73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		32,681.74 €		32,681.74 €	28,446.56 €	1,770,529.40 €	1,189.87 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		32,681.74 €		32,681.74 €	27,957.31 €	1,798,486.71 €	1,074.36 €	73,785.20 €		73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		32,681.74 €	595,000.00 €	627,681.74 €	527,709.99 €	2,326,196.70 €	1,250.64 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		32,681.74 €		32,681.74 €	27,003.90 €	2,353,200.60 €	1,150.15 €	73,785.20 €		73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		32,681.74 €		32,681.74 €	26,539.46 €	2,379,740.07 €	1,066.19 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		32,681.74 €		32,681.74 €	26,083.01 €	2,405,823.08 €	994.96 €	73,785.20 €		73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		32,681.74 €		32,681.74 €	25,634.41 €	2,431,457.49 €	933.74 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		32,681.74 €	350,000.00 €	382,681.74 €	294,999.63 €	2,726,457.12 €	977.22 €	73,785.20 €		73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		32,681.74 €		32,681.74 €	24,760.22 €	2,751,217.34 €	924.47 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		32,681.74 €		32,681.74 €	24,334.37 €	2,775,551.70 €	877.78 €	73,785.20 €		73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		32,681.74 €		32,681.74 €	23,915.84 €	2,799,467.54 €	836.16 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		32,681.74 €		32,681.74 €	23,504.51 €	2,822,972.06 €	798.80 €	73,785.20 €		73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		32,681.74 €	1,146,400.00 €	1,179,081.74 €	833,403.95 €	3,656,376.01 €	982.90 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		32,681.74 €		32,681.74 €	22,702.95 €	3,679,078.96 €	941.90 €	73,785.20 €		73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		32,681.74 €		32,681.74 €	22,312.49 €	3,701,391.45 €	904.54 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		32,681.74 €	32,550.00 €	65,231.74 €	43,769.07 €	3,745,160.52 €	875.45 €	73,785.20 €		73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		32,681.74 €		32,681.74 €	21,551.58 €	3,766,712.10 €	843.80 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		32,681.74 €	350,000.00 €	382,681.74 €	248,014.63 €	4,014,726.73 €	863.38 €	73,785.20 €		73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		32,681.74 €		32,681.74 €	20,816.62 €	4,035,543.35 €	834.48 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		32,681.74 €		32,681.74 €	20,458.60 €	4,056,001.95 €	807.65 €	73,785.20 €		73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		32,681.74 €		32,681.74 €	20,106.73 €	4,076,108.68 €	782.66 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		32,681.74 €		32,681.74 €	19,760.91 €	4,095,869.60 €	759.34 €	73,785.20 €		73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		32,681.74 €	595,000.00 €	627,681.74 €	372,998.39 €	4,468,867.99 €	800.87 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 30 Cash flow for scenario 3 – PV+hydrogen+battery

	SUGGESTED SOLUTION							CURRENT SOLUTION					
year	capex (€)	opex (€)	replacement	tot costs	net present c	NPV	Unit costs	opex (€)	replacemer	tot costs	net present c	NPV	Unit costs
0	872,600.00 €			872,600.00 €	872,600.00 €	872,600.00 €				0.00 €	0.00 €	0.00 €	
1		30,325.22 €		30,325.22 €	29,803.66 €	902,403.66 €	4,851.63 €	73,785.20 €		73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		30,325.22 €		30,325.22 €	29,291.06 €	931,694.72 €	2,504.56 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		30,325.22 €		30,325.22 €	28,787.29 €	960,482.01 €	1,721.29 €	73,785.20 €		73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		30,325.22 €		30,325.22 €	28,292.17 €	988,774.18 €	1,329.00 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		30,325.22 €	350,000.00 €	380,325.22 €	348,724.96 €	1,337,499.15 €	1,438.17 €	73,785.20 €		73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		30,325.22 €		30,325.22 €	27,327.35 €	1,364,826.49 €	1,222.96 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		30,325.22 €		30,325.22 €	26,857.34 €	1,391,683.84 €	1,068.88 €	73,785.20 €		73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		30,325.22 €		30,325.22 €	26,395.42 €	1,418,079.26 €	953.01 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		30,325.22 €		30,325.22 €	25,941.45 €	1,444,020.71 €	862.62 €	73,785.20 €		73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		30,325.22 €	382,550.00 €	412,875.22 €	347,116.01 €	1,791,136.72 €	962.98 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		30,325.22 €		30,325.22 €	25,056.79 €	1,816,193.50 €	887.68 €	73,785.20 €		73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		30,325.22 €		30,325.22 €	24,625.84 €	1,840,819.34 €	824.74 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		30,325.22 €		30,325.22 €	24,202.30 €	1,865,021.63 €	771.31 €	73,785.20 €		73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		30,325.22 €		30,325.22 €	23,786.04 €	1,888,807.67 €	725.35 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		30,325.22 €	350,000.00 €	380,325.22 €	293,183.05 €	2,181,990.72 €	782.08 €	73,785.20 €		73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		30,325.22 €		30,325.22 €	22,974.88 €	2,204,965.61 €	740.92 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		30,325.22 €		30,325.22 €	22,579.74 €	2,227,545.34 €	704.47 €	73,785.20 €		73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		30,325.22 €		30,325.22 €	22,191.39 €	2,249,736.73 €	671.96 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		30,325.22 €		30,325.22 €	21,809.72 €	2,271,546.45 €	642.77 €	73,785.20 €		73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		30,325.22 €	933,950.00 €	964,275.22 €	681,573.43 €	2,953,119.87 €	793.85 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		30,325.22 €		30,325.22 €	21,065.96 €	2,974,185.83 €	761.44 €	73,785.20 €		73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		30,325.22 €		30,325.22 €	20,703.64 €	2,994,889.47 €	731.89 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		30,325.22 €		30,325.22 €	20,347.56 €	3,015,237.04 €	704.82 €	73,785.20 €		73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		30,325.22 €		30,325.22 €	19,997.60 €	3,035,234.64 €	679.94 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		30,325.22 €	350,000.00 €	380,325.22 €	246,487.37 €	3,281,722.02 €	705.75 €	73,785.20 €		73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		30,325.22 €		30,325.22 €	19,315.64 €	3,301,037.66 €	682.60 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		30,325.22 €		30,325.22 €	18,983.43 €	3,320,021.09 €	661.10 €	73,785.20 €		73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		30,325.22 €		30,325.22 €	18,656.93 €	3,338,678.02 €	641.07 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		30,325.22 €		30,325.22 €	18,336.05 €	3,357,014.07 €	622.36 €	73,785.20 €		73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		30,325.22 €	382,550.00 €	412,875.22 €	245,350.12 €	3,602,364.20 €	645.58 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 31 Cash flow for scenario 2 – PV+hydrogen

	SUGGESTED SOLUTION							CURRENT SOLUTION					
year	capex (€)	opex (€)	replacement	tot costs	net present (	NPV	Unit costs	opex (€)	replacemen	tot costs	net present (	NPV	Unit costs
0	545,600.00 €			545,600.00 €	545,600.00 €	545,600.00 €				0.00 €	0.00 €	0.00 €	
1		27,498.82 €		27,498.82 €	27,025.87 €	572,625.87 €	3,078.63 €	73,785.20 €		73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		27,498.82 €		27,498.82 €	26,561.05 €	599,186.92 €	1,610.72 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		27,498.82 €		27,498.82 €	26,104.23 €	625,291.15 €	1,120.59 €	73,785.20 €		73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		27,498.82 €		27,498.82 €	25,655.26 €	650,946.41 €	874.93 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		27,498.82 €		27,498.82 €	25,214.02 €	676,160.43 €	727.05 €	73,785.20 €		73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		27,498.82 €		27,498.82 €	24,780.36 €	700,940.79 €	628.08 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		27,498.82 €		27,498.82 €	24,354.16 €	725,294.95 €	557.06 €	73,785.20 €		73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		27,498.82 €		27,498.82 €	23,935.29 €	749,230.24 €	503.51 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		27,498.82 €		27,498.82 €	23,523.63 €	772,753.87 €	461.62 €	73,785.20 €		73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		27,498.82 €	245,000.00 €	272,498.82 €	229,097.55 €	1,001,851.43 €	538.63 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		27,498.82 €	32,550.00 €	60,048.82 €	49,616.47 €	1,051,467.90 €	513.91 €	73,785.20 €		73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		27,498.82 €		27,498.82 €	22,330.64 €	1,073,798.54 €	481.09 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		27,498.82 €		27,498.82 €	21,946.57 €	1,095,745.11 €	453.16 €	73,785.20 €		73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		27,498.82 €		27,498.82 €	21,569.11 €	1,117,314.22 €	429.08 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		27,498.82 €		27,498.82 €	21,198.14 €	1,138,512.37 €	408.07 €	73,785.20 €		73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		27,498.82 €		27,498.82 €	20,833.56 €	1,159,345.92 €	389.57 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		27,498.82 €		27,498.82 €	20,475.24 €	1,179,821.16 €	373.12 €	73,785.20 €		73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		27,498.82 €		27,498.82 €	20,123.09 €	1,199,944.25 €	358.41 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		27,498.82 €		27,498.82 €	19,776.99 €	1,219,721.24 €	345.14 €	73,785.20 €		73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		27,498.82 €	484,400.00 €	511,898.82 €	361,822.67 €	1,581,543.91 €	425.15 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		27,498.82 €		27,498.82 €	19,102.55 €	1,600,646.46 €	409.79 €	73,785.20 €		73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		27,498.82 €	32,550.00 €	60,048.82 €	40,996.55 €	1,641,643.01 €	401.18 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		27,498.82 €		27,498.82 €	18,451.11 €	1,660,094.12 €	388.05 €	73,785.20 €		73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		27,498.82 €		27,498.82 €	18,133.77 €	1,678,227.89 €	375.95 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		27,498.82 €		27,498.82 €	17,821.89 €	1,696,049.77 €	364.74 €	73,785.20 €		73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		27,498.82 €		27,498.82 €	17,515.37 €	1,713,565.14 €	354.34 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		27,498.82 €		27,498.82 €	17,214.12 €	1,730,779.26 €	344.64 €	73,785.20 €		73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		27,498.82 €		27,498.82 €	16,918.05 €	1,747,697.31 €	335.58 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		27,498.82 €		27,498.82 €	16,627.08 €	1,764,324.39 €	327.09 €	73,785.20 €		73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		27,498.82 €	245,000.00 €	272,498.82 €	161,931.78 €	1,926,256.18 €	345.21 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 32 Cash flow for scenario 1 – PV+battery

The following plot (fig. 33) shows trends comparison over lifetime span for the different configurations:

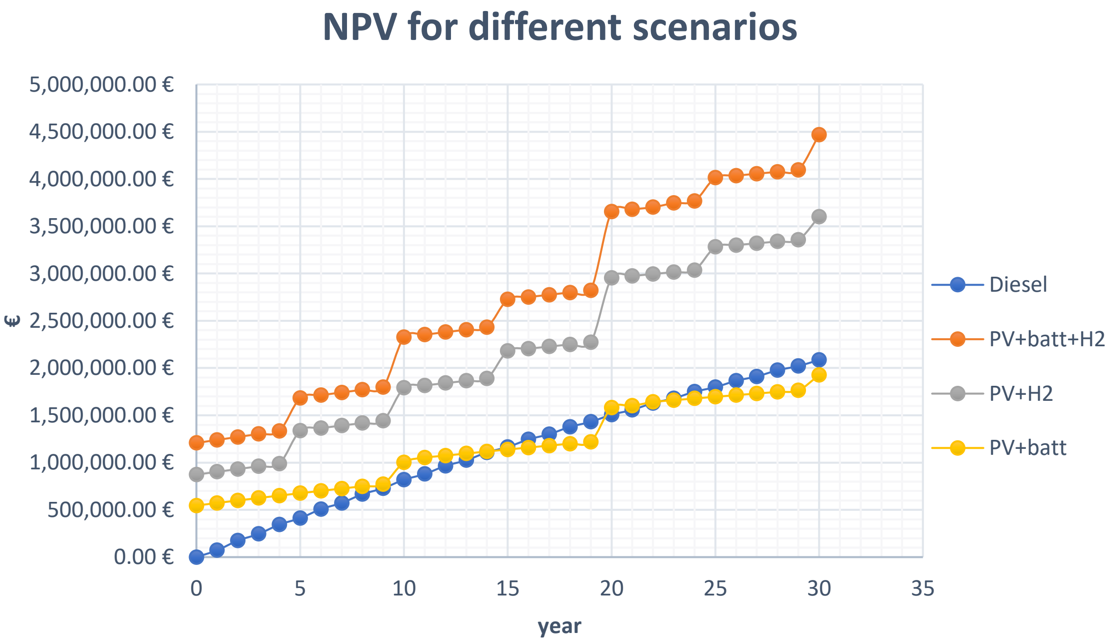


Figure 33 Cost trend for different scenarios – PV case

Benefiting from the cash flows, it's easy to calculate the LCOE according to (2).

Table 6 LCOE for PV case

	Scenario 3	Scenario 2	Scenario 1
Load (MWh)	186.362	186.362	186.362
LCOE (€/MWh)	991.4682	799.225	427.361

Observing cost trends and LCOE values, strategy 1 (PV+ battery) turns out to be the best among the three studied. Although the technical performances are the worst (see paragraph 2.7), LCOE is less than half than scenario 3. This suggests that hydrogen technologies costs have very high impact on the LCOE calculation. Strategy 1 is more profitable also than diesel only over long period, since after 22 years its curve is always below. Scenario 3 is the most cost effective, while scenario 2 LCOE is in the middle. High discontinuities in the curves are due to components replacement costs, especially accentuated in the 20th years of lifetime.

2.10.4 Sensitivity analysis on PV size

In this paragraph the simulations will be repeated varying PV size, in order to see if the LCOE could be further minimized for a hydrogen storage scenario. Only strategy 2 will be considered in this part, since it has proven to guarantee lower LCOE as showed in previous paragraph. Other devices sizes will be kept constant as in scenario 2 of previous analysis. Four discrete sizes are considered (150 kW, 180 kW, 210 kW, 250 kW), and the following plot (fig. 34) shows how LCOE varies:

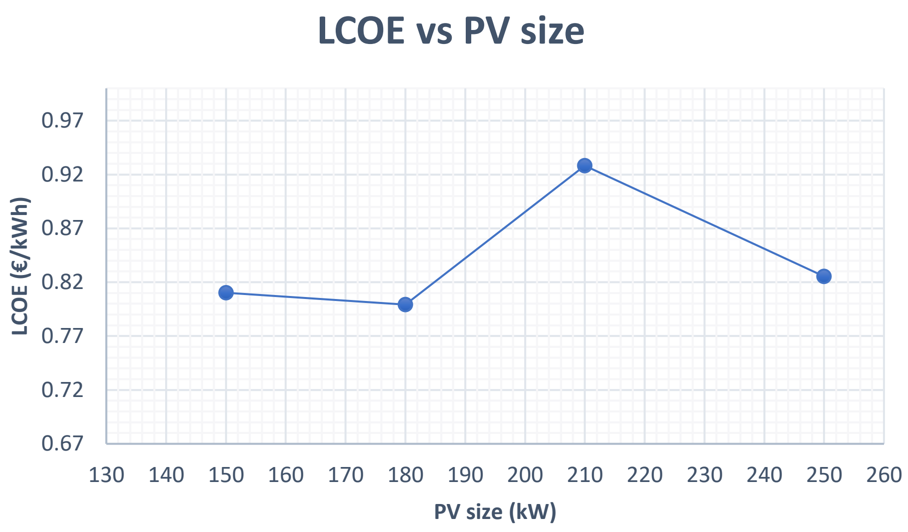


Figure 34 Sensitivity analysis on PV size

The first choice of PV size, deriving from preliminary optimization, confirms to be the best option. Reducing the nominal size of photovoltaic panels the LCOE increases slightly, while moving from 180 to 210 kW it increases significantly and then reduces again in correspondence of 250 kW. This behaviour is due to reduced operative costs that this configuration allows, because increasing RES capacity diesel operation hours reduce, with its associated costs. Such reduction, however, doesn't compensate the increase of capital costs.

2.10.5 Wind energy case results

The same economical outcomes displayed for PV case are now shown for the three wind energy scenarios (figs. 35 to 37), using the same notation.

year	SUGGESTED SOLUTION capex (€)	opex (€)	replacement	tot costs	net present co	NPV	Unit costs	CURRENT SOLUTION opex (€)	replacemer	tot costs	present costs	NPV	Unit costs
0	1,132,000.00 €			1,132,000.00 €	1,132,000.00 €	1,132,000.00 €				0.00 €	0.00 €	0.00 €	
1		26,141.52 €		26,141.52 €	25,691.91 €	1,157,691.91 €	6,224.15 €	73,785.20 €		73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		26,141.52 €		26,141.52 €	25,250.04 €	1,182,941.95 €	3,179.95 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		26,141.52 €		26,141.52 €	24,815.76 €	1,207,757.71 €	2,164.44 €	73,785.20 €		73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		26,141.52 €		26,141.52 €	24,388.95 €	1,232,146.66 €	1,656.11 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		26,141.52 €	350,000.00 €	376,141.52 €	344,888.88 €	1,577,035.54 €	1,695.74 €	73,785.20 €		73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		26,141.52 €		26,141.52 €	23,557.24 €	1,600,592.77 €	1,434.22 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		26,141.52 €		26,141.52 €	23,152.07 €	1,623,744.85 €	1,247.12 €	73,785.20 €		73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		26,141.52 €		26,141.52 €	22,753.88 €	1,646,498.73 €	1,106.52 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		26,141.52 €		26,141.52 €	22,362.54 €	1,668,861.27 €	996.93 €	73,785.20 €		73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		26,141.52 €	595,000.00 €	621,141.52 €	522,211.44 €	2,191,072.71 €	1,178.00 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		26,141.52 €		26,141.52 €	21,599.93 €	2,212,672.63 €	1,081.46 €	73,785.20 €		73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		26,141.52 €		26,141.52 €	21,228.43 €	2,233,901.06 €	1,000.85 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		26,141.52 €		26,141.52 €	20,863.32 €	2,254,764.38 €	932.49 €	73,785.20 €		73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		26,141.52 €		26,141.52 €	20,504.49 €	2,275,268.87 €	873.76 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		26,141.52 €	350,000.00 €	376,141.52 €	289,957.94 €	2,565,226.81 €	919.44 €	73,785.20 €		73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		26,141.52 €		26,141.52 €	19,805.24 €	2,585,032.05 €	868.63 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		26,141.52 €		26,141.52 €	19,464.61 €	2,604,496.67 €	823.69 €	73,785.20 €		73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		26,141.52 €		26,141.52 €	19,129.84 €	2,623,626.50 €	783.64 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		26,141.52 €		26,141.52 €	18,800.82 €	2,642,427.33 €	747.72 €	73,785.20 €		73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		26,141.52 €	1,075,750.00 €	1,101,891.52 €	778,844.01 €	3,421,271.34 €	919.70 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		26,141.52 €		26,141.52 €	18,159.67 €	3,439,431.01 €	880.55 €	73,785.20 €		73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		26,141.52 €		26,141.52 €	17,847.35 €	3,457,278.36 €	844.89 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		26,141.52 €		26,141.52 €	17,540.39 €	3,474,818.75 €	812.25 €	73,785.20 €		73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		26,141.52 €		26,141.52 €	17,238.71 €	3,492,057.46 €	782.27 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		26,141.52 €	350,000.00 €	376,141.52 €	243,775.93 €	3,735,833.39 €	803.41 €	73,785.20 €		73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		26,141.52 €		26,141.52 €	16,650.83 €	3,752,484.23 €	775.95 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		26,141.52 €		26,141.52 €	16,364.46 €	3,768,848.68 €	750.47 €	73,785.20 €		73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		26,141.52 €		26,141.52 €	16,083.00 €	3,784,931.68 €	726.75 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		26,141.52 €		26,141.52 €	15,806.39 €	3,800,738.08 €	704.62 €	73,785.20 €		73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		26,141.52 €	595,000.00 €	621,141.52 €	369,111.88 €	4,169,849.96 €	747.28 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 36 Cash flow for scenario 3 – wind+hydrogen+battery

year	SUGGESTED SOLUTION capex (€)	opex (€)	replacement	tot costs	net present c	NPV	Unit costs	CURRENT SOLUTION opex (€)	replacemer	tot costs	net present c	NPV	Unit costs
0	851,000.00 €			851,000.00 €	851,000.00 €	851,000.00 €		0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
1		18,878.12 €		18,878.12 €	18,553.44 €	869,553.44 €	4,675.02 €	73,785.20 €	0.00 €	73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		18,878.12 €		18,878.12 €	18,234.33 €	887,787.77 €	2,386.53 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		18,878.12 €		18,878.12 €	17,920.72 €	905,708.49 €	1,623.13 €	73,785.20 €	0.00 €	73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		18,878.12 €		18,878.12 €	17,612.50 €	923,321.00 €	1,241.02 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		18,878.12 €	350,000.00 €	368,878.12 €	338,228.97 €	1,261,549.97 €	1,356.51 €	73,785.20 €	0.00 €	73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		18,878.12 €		18,878.12 €	17,011.88 €	1,278,561.85 €	1,145.66 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		18,878.12 €		18,878.12 €	16,719.29 €	1,295,281.14 €	994.84 €	73,785.20 €	0.00 €	73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		18,878.12 €		18,878.12 €	16,431.73 €	1,311,712.87 €	881.53 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		18,878.12 €		18,878.12 €	16,149.13 €	1,327,862.00 €	793.23 €	73,785.20 €	0.00 €	73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		18,878.12 €	350,000.00 €	368,878.12 €	310,126.39 €	1,637,988.38 €	880.64 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		18,878.12 €		18,878.12 €	15,598.40 €	1,653,586.79 €	808.20 €	73,785.20 €	0.00 €	73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		18,878.12 €		18,878.12 €	15,330.13 €	1,668,916.91 €	747.72 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		18,878.12 €		18,878.12 €	15,066.46 €	1,683,983.38 €	696.44 €	73,785.20 €	0.00 €	73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		18,878.12 €		18,878.12 €	14,807.34 €	1,698,790.71 €	652.38 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		18,878.12 €	350,000.00 €	368,878.12 €	284,358.77 €	1,983,149.48 €	710.81 €	73,785.20 €	0.00 €	73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		18,878.12 €		18,878.12 €	14,302.37 €	1,997,451.86 €	671.19 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		18,878.12 €		18,878.12 €	14,056.39 €	2,011,508.24 €	636.15 €	73,785.20 €	0.00 €	73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		18,878.12 €		18,878.12 €	13,814.63 €	2,025,322.87 €	604.94 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		18,878.12 €		18,878.12 €	13,577.03 €	2,038,899.90 €	576.94 €	73,785.20 €	0.00 €	73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		18,878.12 €	794,750.00 €	813,628.12 €	575,092.35 €	2,613,992.25 €	702.69 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		18,878.12 €		18,878.12 €	13,114.02 €	2,627,106.28 €	672.58 €	73,785.20 €	0.00 €	73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		18,878.12 €		18,878.12 €	12,888.48 €	2,639,994.75 €	645.16 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		18,878.12 €		18,878.12 €	12,666.81 €	2,652,661.56 €	620.07 €	73,785.20 €	0.00 €	73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		18,878.12 €		18,878.12 €	12,448.95 €	2,665,110.51 €	597.02 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		18,878.12 €	350,000.00 €	368,878.12 €	239,068.55 €	2,904,179.06 €	624.55 €	73,785.20 €	0.00 €	73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		18,878.12 €		18,878.12 €	12,024.41 €	2,916,203.48 €	603.02 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		18,878.12 €		18,878.12 €	11,817.61 €	2,928,021.08 €	583.04 €	73,785.20 €	0.00 €	73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		18,878.12 €		18,878.12 €	11,614.35 €	2,939,635.43 €	564.45 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		18,878.12 €		18,878.12 €	11,414.60 €	2,951,050.03 €	547.10 €	73,785.20 €	0.00 €	73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		18,878.12 €	350,000.00 €	368,878.12 €	219,204.95 €	3,170,254.98 €	568.15 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 35 Cash flow for scenario 2 – wind+hydrogen

	SUGGESTED SOLUTION							CURRENT SOLUTION					
year	capex (€)	opex (€)	replacement	tot costs	net present (	NPV	Unit costs	opex (€)	replacemen	tot costs	net present (	NPV	Unit costs
0	470,000.00 €			470,000.00 €	470,000.00 €	470,000.00 €	#DIV/0!	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €	0.00 €
1		21,708.20 €		21,708.20 €	21,334.84 €	491,334.84 €	2,641.59 €	73,785.20 €	0.00 €	73,785.20 €	72,516.17 €	72,516.17 €	389.87 €
2		21,708.20 €		21,708.20 €	20,967.90 €	512,302.74 €	1,377.16 €	73,785.20 €	32,550.00 €	106,335.20 €	102,708.93 €	175,225.10 €	471.04 €
3		21,708.20 €		21,708.20 €	20,607.28 €	532,910.02 €	955.04 €	73,785.20 €	0.00 €	73,785.20 €	70,043.20 €	245,268.30 €	439.55 €
4		21,708.20 €		21,708.20 €	20,252.85 €	553,162.87 €	743.50 €	73,785.20 €	32,550.00 €	106,335.20 €	99,206.33 €	344,474.63 €	463.00 €
5		21,708.20 €		21,708.20 €	19,904.52 €	573,067.39 €	616.20 €	73,785.20 €	0.00 €	73,785.20 €	67,654.57 €	412,129.21 €	443.15 €
6		21,708.20 €		21,708.20 €	19,562.18 €	592,629.57 €	531.03 €	73,785.20 €	32,550.00 €	106,335.20 €	95,823.17 €	507,952.38 €	455.15 €
7		21,708.20 €		21,708.20 €	19,225.73 €	611,855.31 €	469.93 €	73,785.20 €	0.00 €	73,785.20 €	65,347.40 €	573,299.78 €	440.32 €
8		21,708.20 €		21,708.20 €	18,895.07 €	630,750.37 €	423.89 €	73,785.20 €	32,550.00 €	106,335.20 €	92,555.39 €	665,855.17 €	447.48 €
9		21,708.20 €		21,708.20 €	18,570.09 €	649,320.47 €	387.89 €	73,785.20 €	0.00 €	73,785.20 €	63,118.91 €	728,974.08 €	435.47 €
10		21,708.20 €	277,550.00 €	299,258.20 €	251,594.93 €	900,915.39 €	484.36 €	73,785.20 €	32,550.00 €	106,335.20 €	89,399.04 €	818,373.13 €	439.99 €
11		21,708.20 €		21,708.20 €	17,936.81 €	918,852.21 €	449.10 €	73,785.20 €	0.00 €	73,785.20 €	60,966.42 €	879,339.54 €	429.78 €
12		21,708.20 €		21,708.20 €	17,628.32 €	936,480.52 €	419.57 €	73,785.20 €	32,550.00 €	106,335.20 €	86,350.34 €	965,689.88 €	432.66 €
13		21,708.20 €		21,708.20 €	17,325.13 €	953,805.65 €	394.46 €	73,785.20 €	0.00 €	73,785.20 €	58,887.32 €	1,024,577.20 €	423.73 €
14		21,708.20 €		21,708.20 €	17,027.15 €	970,832.80 €	372.82 €	73,785.20 €	32,550.00 €	106,335.20 €	83,405.60 €	1,107,982.80 €	425.49 €
15		21,708.20 €		21,708.20 €	16,734.30 €	987,567.10 €	353.97 €	73,785.20 €	0.00 €	73,785.20 €	56,879.14 €	1,164,861.94 €	417.51 €
16		21,708.20 €		21,708.20 €	16,446.49 €	1,004,013.58 €	337.37 €	73,785.20 €	32,550.00 €	106,335.20 €	80,561.28 €	1,245,423.22 €	418.49 €
17		21,708.20 €		21,708.20 €	16,163.62 €	1,020,177.21 €	322.64 €	73,785.20 €	0.00 €	73,785.20 €	54,939.43 €	1,300,362.65 €	411.25 €
18		21,708.20 €		21,708.20 €	15,885.62 €	1,036,062.83 €	309.46 €	73,785.20 €	32,550.00 €	106,335.20 €	77,813.96 €	1,378,176.61 €	411.64 €
19		21,708.20 €		21,708.20 €	15,612.41 €	1,051,675.24 €	297.59 €	73,785.20 €	0.00 €	73,785.20 €	53,065.87 €	1,431,242.49 €	404.99 €
20		21,708.20 €	446,300.00 €	468,008.20 €	330,799.70 €	1,382,474.94 €	371.63 €	73,785.20 €	32,550.00 €	106,335.20 €	75,160.33 €	1,506,402.82 €	404.95 €
21		21,708.20 €		21,708.20 €	15,079.99 €	1,397,554.93 €	357.80 €	73,785.20 €	0.00 €	73,785.20 €	51,256.21 €	1,557,659.03 €	398.79 €
22		21,708.20 €		21,708.20 €	14,820.63 €	1,412,375.56 €	345.16 €	73,785.20 €	32,550.00 €	106,335.20 €	72,597.20 €	1,630,256.23 €	398.40 €
23		21,708.20 €		21,708.20 €	14,565.73 €	1,426,941.29 €	333.55 €	73,785.20 €	0.00 €	73,785.20 €	49,508.26 €	1,679,764.49 €	392.65 €
24		21,708.20 €		21,708.20 €	14,315.21 €	1,441,256.50 €	322.86 €	73,785.20 €	32,550.00 €	106,335.20 €	70,121.47 €	1,749,885.96 €	392.00 €
25		21,708.20 €		21,708.20 €	14,069.00 €	1,455,325.50 €	312.97 €	73,785.20 €	0.00 €	73,785.20 €	47,819.92 €	1,797,705.87 €	386.60 €
26		21,708.20 €		21,708.20 €	13,827.03 €	1,469,152.53 €	303.79 €	73,785.20 €	32,550.00 €	106,335.20 €	67,730.17 €	1,865,436.05 €	385.74 €
27		21,708.20 €		21,708.20 €	13,589.22 €	1,482,741.75 €	295.25 €	73,785.20 €	0.00 €	73,785.20 €	46,189.15 €	1,911,625.20 €	380.65 €
28		21,708.20 €		21,708.20 €	13,355.50 €	1,496,097.25 €	287.27 €	73,785.20 €	32,550.00 €	106,335.20 €	65,420.42 €	1,977,045.62 €	379.62 €
29		21,708.20 €		21,708.20 €	13,125.80 €	1,509,223.05 €	279.80 €	73,785.20 €	0.00 €	73,785.20 €	44,614.00 €	2,021,659.62 €	374.80 €
30		21,708.20 €	277,550.00 €	299,258.20 €	177,833.48 €	1,687,056.53 €	302.34 €	73,785.20 €	32,550.00 €	106,335.20 €	63,189.44 €	2,084,849.06 €	373.63 €

Figure 37 Cash flow for scenario 1 – wind+battery

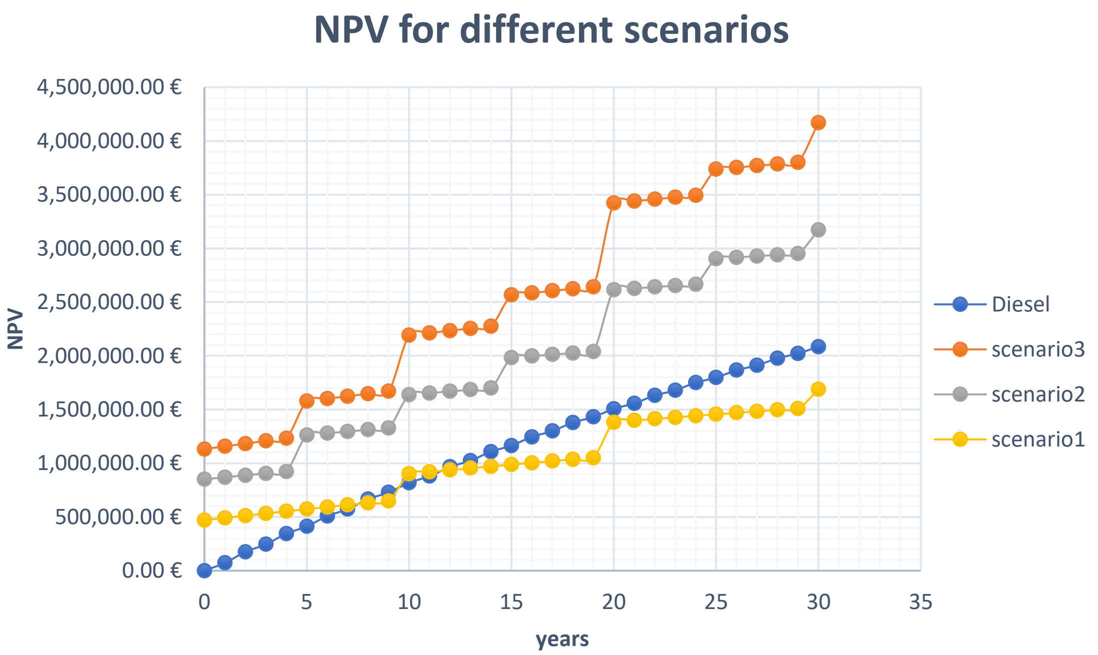


Figure 38 Cost trend for different scenarios – wind energy case

Table 7 LCOE for wind case

	Scenario 1	Scenario 2	Scenario 3
Load (MWh)	186.362	186.362	186.362
LCOE (€/MWh)	925.128	703.356	374.292

The first comment is that all the values are lower than PV case, most of all for scenario 2, with a difference of 95.87 €/MWh in favour of wind case. Generally, the trend is the same of photovoltaics case: PV with battery is the best solution over long time, scenario 3 turns out to be the more expensive while hydrogen tank as only storage is in the middle.

2.10.6 Sensitivity analysis on wind farm size

The same analysis led for PV is repeated for wind energy, carrying out a sensitivity analysis on RES size (wind farm in this case) of the H2-based best scenario individuated following the economic analysis (scenario 2).

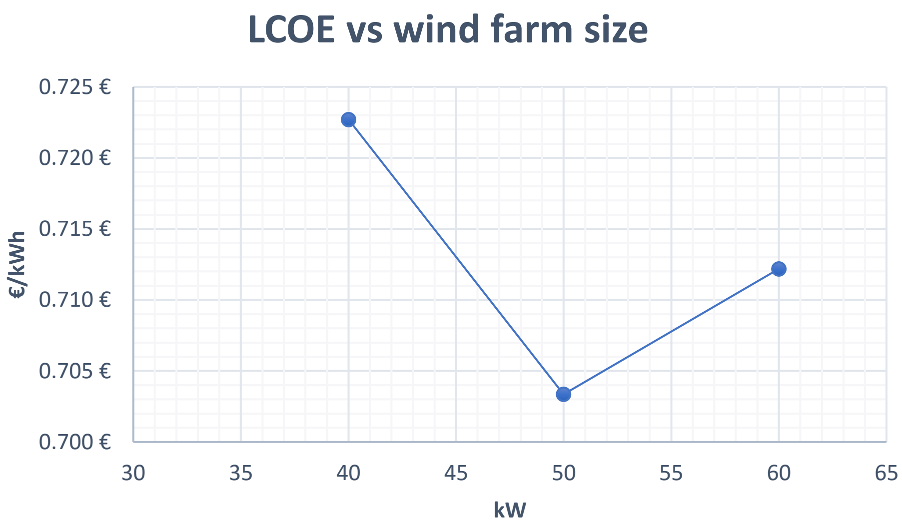


Figure 39 Sensitivity analysis on wind farm size

Three simulations have been compared, 40 kW, 50 kW and 60 kW. The results, showed in fig.39, confirm 50 kW being the best choice. What happens increasing RES size is that the additional costs (capex) prevail on the benefits, penalizing the LCOE. On the other hand, a reduction of RES size means less costs for the wind turbine system but more need of diesel, increasing operating costs, with the same final effect.

2.10.7 PV and wind combinations

In this paragraph combinations of PV and wind turbines will be analyzed in a P2P system to supply energy to the community. This choice could appear unnecessary, since wind resource has been proven to be more promising. However, the distribution of RES production could affect the effectiveness of hydrogen storage system. Proven that a RES/battery system is already more profitable than current status, the strategy analysed will be the one H_2-basis revealed the best in previous analysis, that is strategy 2. Three hybrid system will be studied:

- 75% PV and 25% wind (45 kW PV, 10 kW wind)
- 50% PV and 50% wind (90 kW PV, 20 kW wind)
- 25% PV and 75% wind (135 kW PV, 30 kW wind)

Whereas the rate is referred to the system size adopted in PV and wind only paragraphs. The size of other components is kept constant.

Following the steps of the analysis, hereafter the LCOE for the different combinations are reported:

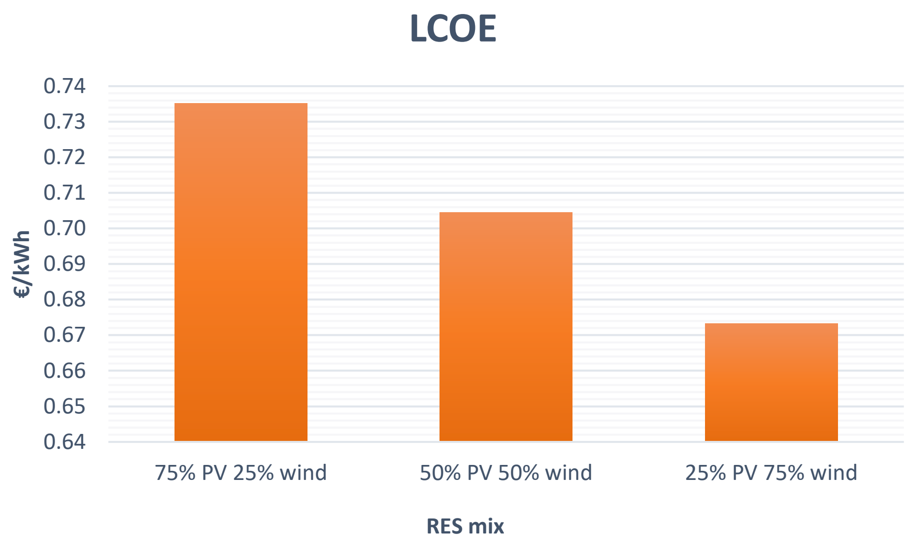


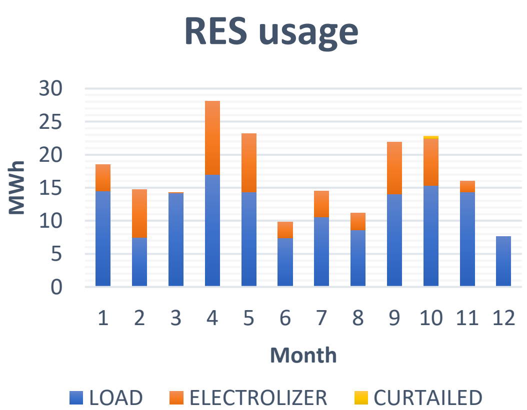
Figure 40 LCOE for different hybrid RES+hydrogen systems

The option with 25% of solar PV energy and 75% of wind energy turns out to be the most promising in terms of minimizing LCOE (0.673 €/kWh), it will be thus analyzed in depth.

The following figure 41 resumes the technical outcomes of this configuration:

TOT RES (MWh)	202.644
% LOAD	72%
% ELECTROLIZER	28%
% CURT	0%

TOT Load (MWh)	186.362
% RES	78%
% FC	14%
% EXT	8%



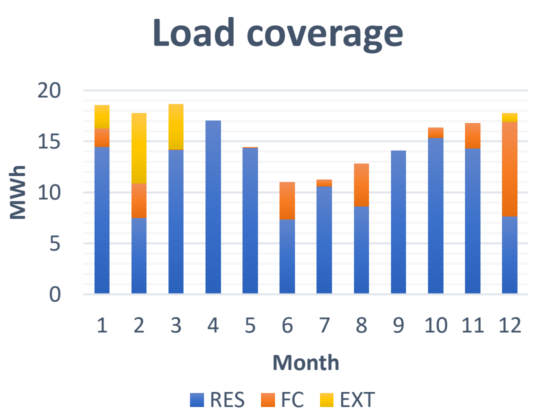


Figure 41 RES (25% PV 75% wind) usage and load coverage for scenario 2

In this scenario energy curtailment is very low, just 405.6 kWh in October, when in the face of a quite high load, wind is heavy and there is still a bit of solar irradiance not exploited. The external needing, 8% of the total load, is slightly higher than corresponding wind-only configuration, but lower than PV-only. It occurs mainly during the first months of the year, when RES is low and storage is empty. Observing the levelized cost of energy (fig. 40), it is worth to note that this is the best configuration found all over this case study, being 0.126 €/kWh lower than PV-only case and 0.030 €/kWh lower than wind-only case.

2.11 Future perspective trend costs

In this paragraph, the economic analysis done above will be carried out trying to predict devices costs for future years, in order to see if the H_2-based P2P solutions, proved to be not feasible nowadays compared to more traditional solutions, could turn out to be the best option next years.

This part of the work has required the analysis of papers and document concerning trends for future years. A crucial factor in this matter is the data newness (e.g. year of publication), since this is a sector in fast changing. Nevertheless, a great incertitude is intrinsic in such analysis, for these reasons the assumptions and the considerations done have been reported in the next paragraph, component by component. Missing data have been replaced with reasonable choices.

2.11.1 Components cost projections

PV panels

For this component a working paper by UK Energy Research Centre (UKERC) has been considered [55]. In this report cost trajectories as estimated by several studies commissioned by UK Government are reported. The cost trend curves are distinguished by small, medium or large size PV system. The prices are referred to UK market. In order to be consistent with the current cost used in the economic analysis, the projection by Department of Energy and Climate Change (DEPCC) of London seemed the most reasonable. Considering the current GBP-Euro exchange (1 GBP= 1.1 €, June 2019), the price of PV panels is estimated to be 965 €/kWh in 2025 and 900 €/kWh in 2030. Operative costs are kept as 3% of capex.

Wind turbine

Expectations on wind turbine future prices are based on a work dated June 2016 led by LBNL (Lawrence Berkely National Laboratory) and NREL (National Renewable Energy Laboratory) [56]. This work, which gathers several wind industry experts, underlines trend cost and uncertainties for different wind energy scenarios. For onshore (land-based) case, a reduction of capex of 12 % is predicted and an increase of 10% in project life. Concerning opex, a reduction of 9% is confirmed by a more recent study referred to US land based wind power plants [57].

Fuel cell

Since fuel cells represent an emerging technology, a great potential in cost reduction is foreseen. In [58] empirical data are presented for Japanese market PEMFC and experience curves are fitted to these data. The resulting curves predict the fall in fuel cell prices depending on the number of units and different probabilities scenario. Specifically, in the cited paper a fan chart on logarithmic scale is used to evidence the spread in the possible outcomes. Ten equally spaced percentiles are plotted as boundaries of the bands. In the present work, in order to be consistent with the price used in the economic analysis (5 €/W), the projection results to be 1.3 €/W in 2025 and 1.12 €/W in 2030 (capex).

Electrolyser

Water electrolysis cost trend is based on an expert elicitation study of 2017 [52]. Expert views estimate that increased R&D funding can reduce capital costs up to 24%, while production scale-up could have an impact of 30%. Specifically, in the paper it is assessed that research into SOECs with lower electrode polarisation resistance or zero-gap ACEs could undermine the projected dominance of PEMEC systems.

Diesel generator

Concerning diesel generators, no cost trends have been found in literature about stationary diesel generators for next years. This could be addresses to a saturated market of a well mature technology. A different procedure has hence been used to estimated prices to 2025 and 2030. Some papers from past years [28], [29] referred to Canadian market have been considered, and a cost prediction has been made considering the percentage reduction in succeeding years.

Diesel price

Diesel price cost prediction has been made on US market, and then reported in Canadian market considering the average difference over the past years. Referring to the Annual Energy Outlook 2019 by EIA [59], [60], containing projections to 2050, a reference case and two sides case (High and low economic growth) are considered to model projections. The former, in this work considered, represents EIA's best assessment of how US and world energy market will operate in next years. After 2018 a rise of diesel fuel price is foreseen. Particularly, the price for 2025 is expected to be 0.92 USD/l while 1.00 USD/l is the price foreseen for 2030. To bring back US diesel price to Canadian one, the percentage difference over the past 5 years has been considered [61], that is +9.3% higher in Canada than in US. Considering the current CAD-USD exchange (1 CAD= 0.76 USD, June 2019), this means a Canadian diesel price of 1.00 CAD/l in 2025 and of 1.09 CAD/l. The last step to have a realistic projection is to consider the cost increase in remote locations. To achieve these, an increase of +8.5% has been considered for Paradise River compared to average Canada price, based on the percentage increase in the past.

Hydrogen storage

Concerning hydrogen tank, the price is supposed not to change in this work. Actually, a large range of cost is found in literature. This is due to the different sizes and technologies of storage. The author expects that a significant cost reduction can be foreseen for high pressure advanced storage technology, while for simpler gas storage, like the one in this work, price drop can be neglected.

Batteries

Landmark for battery future cost is given by a web available document about a 2017 workshop led by IRENA in Düsseldorf [61]. This file contains precious information about performances and cost trend of different kinds of storage technologies. In the present case study, gel lead acid batteries are considered, so that the cost used previously is as much consistent as possible with the mentioned outlook. According to it, a 22% of capex reduction is expected from 2020 to 2025 and a 39% reduction up to 2030. The calendar life will shorten by 1 year in 2025 and 3 years by 2030. O&M costs are considered still as 3% of capex while replacement cost is set to be equal to it.

2.11.2 Outcomes

The following figure 42 depicts the LCOE analysis for 2025, referred to the best RES configuration found for Paradise River case study (25% PV 75% wind):

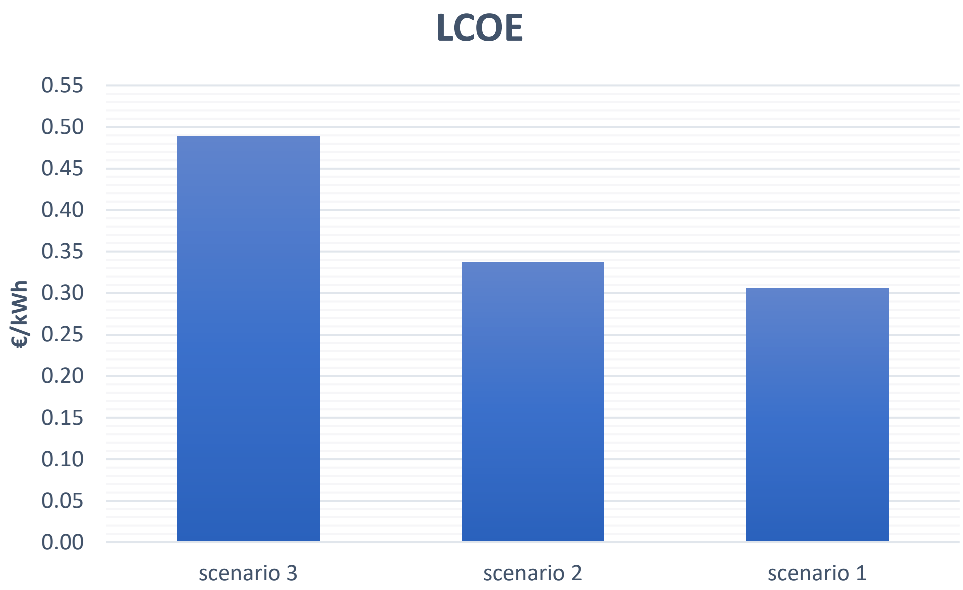


Figure 42 LCOE prediction in 2025

Scenario 1, which envisages the use of RES and battery, remains the best choice in terms of LCOE (0.306 €/kWh). The foreseen LCOE for scenario 2 is 0.337 €/kWh, lower than the option with just diesel (expected to rise to 0.486 €/kWh). Scenario 3 cost, the option minimizing external requirement, drops off to 0.488 €/kWh, but confirms to be still higher than others. Comparing scenario 2 with the analysis done for current days diesel only configuration, a remarkable reduction of 0.336 €/kWh in LCOE is calculated.

The following histograms show the foreseen situation in 2030:

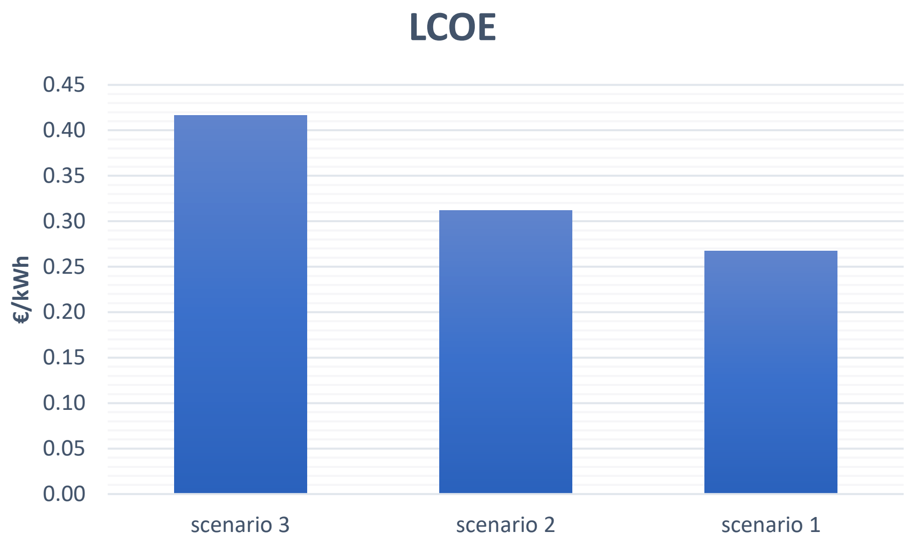


Figure 43 LCOE prediction in 2030

In 2030, according to present prediction, all the 3 proposed solution will have lower LCOE than current solution (diesel only, 0.463 €/kWh). The trend confirms to be the same, with strategy 1 remaining the best choice, but strategy 3 having for the first time a LCOE lower than today's value. Scenario 3 is also the configuration which minimizes the use of diesel, therefore represents the most environmentally friendly option (see Section 4). Being cheaper than diesel in 2030 means being better under both techno economic and environmental point of view. For this reason, it could be particularly attractive for the future (>10 years). The technical details of such configuration are shown in the following figure 44:

TOT RES (MWh)	202.644
% LOAD	72%
% BATTERY	11%
% ELECTROLIZER	14%
% CURT	3%

TOT Load (MWh)	186.362
% RES	78%
% BATTERY	10%
% FC	7%
% EXT	5%

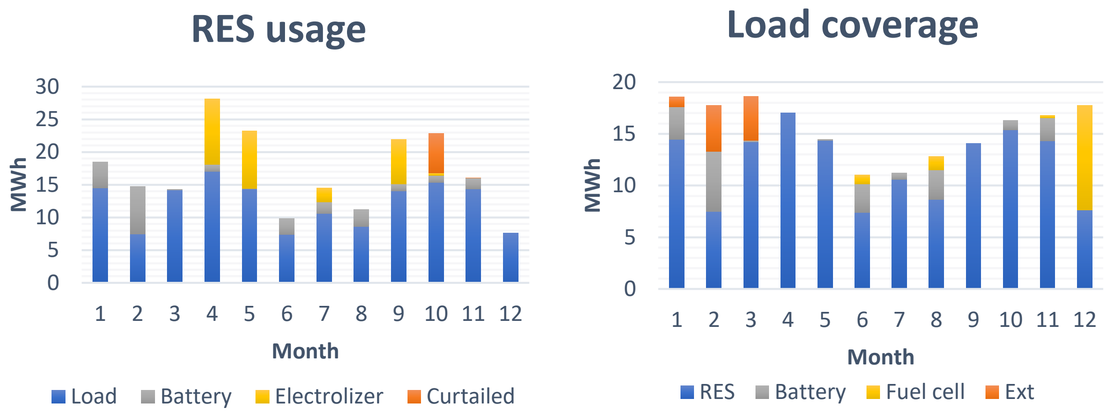


Figure 44 RES usage and load coverage

Clearly, technical data resulting from the analysis are the same achievable nowadays, assuming that the load doesn't change over the time and RES production remain the same[4]. Comparing this configuration with the corresponding scenario 2 (fig. 41), that is just H_2 as storage, external needing is reduced, occurring it just at the beginning of the year. At the same time curtailment increases by 3% because a smaller tank can be used while keeping high SoC with benefits for the economics.

[4] Actually, an interesting idea could be to take action on them, as brought up in Section 5

Section 3 – Colville Lake case study

3.1 Colville Lake community

Colville Lake is a small settlement situated in the province of Northwest Territories (67° 4' 12" N 126° 6' W). People living here, around 150, form a very traditional community based on fishing. The distance from other relevant town (463 mi from Yellowknife) and the presence of the Artic Circle at 31 miles (fig. 45) make Colville Lake a very remote community. The climate is generally harsh being high latitude, with temperature ranging between -30° and 19° along the year. The sky is mostly clear from May to middle September, and midnight sun is experienced during summer. Due to extreme latitude the sun is continuously above the horizon for more than a summer month, but the irradiance is few intense as well. The windiest part of the year run from November to middle June, with average speeds of more than 10 miles per hour [62].

Figure 45 Location of the two communities studied

3.2 Background and current solution

Concerning the energy matter, there is neither electric nor natural gas grid in this territory and population relies on power supplied by diesel generators. In 2013 a project of a solar diesel hybrid system has been proposed for the community. Such step derives from the necessity to substitute diesel generators already present (end of life) and meet the goal of GNWT (Government of the Northwest Territories') in terms of renewable energies. The project, realized in two steps, concerns the installation of 136 kW of PV panels coupled with a 200 kWh battery storage. Three diesel generators, sized 100 and 150 kW, supply the remaining power.

3.3 Load modeling

Another reason driving the realization of the above mentioned project is the community's growing demand for electricity, which increased from 40 kW in 1990 to 160 kW in 2014 (peak demand) [63]. For Colville Lake a different approach has been adopted to mark out the load curve, following the guidelines of Tsamaase et al. in [64]. In the paper in question the load demand profile of a village in Botswana is studied and the relationship between daily hours and consumption is obtained taking advantage of method of least square approximation. The model, other than discriminate two seasons, is worthwhile because takes into account both the household and the commercial consumption. Combining these data with the ones of Colville Lake community an appropriated load profiled has been tracked. In [65] an accurate breakdown of Colville Lake infrastructure profile has been found. Beside the 37 dwellings in the community [44], 1 grocer, 1 health cabin, 1 gymnasuium, 1 lodge/outfitter, 1 accommodation and 1 school exist. The Alaska village calculator [44] allows the calculation of the consumption of each of these infrastructures. However, considering that the load profile model in question allows the distinction between just due kinds of profile (household and commercial), an estimation has been done, coming out that around 10% of the total load is non-residential. In this way the profile curves suggested by the above cited paper have been scaled according to the actual total load and the kind of profile. The curves deriving are shown in figure 46.

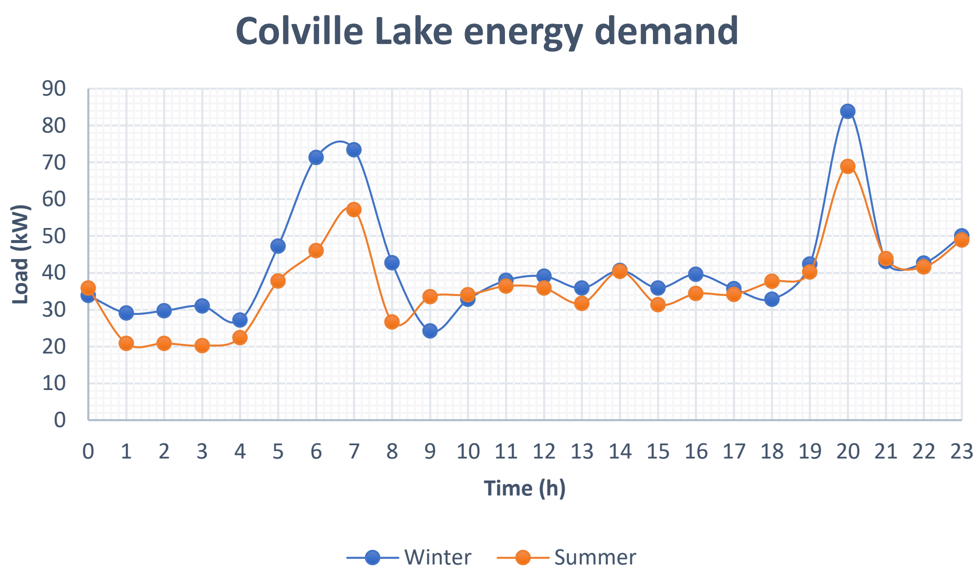


Figure 46 Load profile during warm and cold seasons in Colville Lake

The two profiles already consider weighted average between residential and commercial loads and show similar trend but more accentuated peaks for winter model.

3.4 PV production

In this case study a real operation situation (rather than an ideal one, as in Paradise River case study) has been considered. This is possible because NTCP company, who has installed the current solar/diesel/battery system, makes possible to track the electricity produced by the system on its website with a time step of 15 minutes [66]. This means that instead of estimating the PV production starting from irradiance data, as done for Paradise River, actual data of PV production are available. This powerful tool requires some adjustments to be used in the model used in this work. In the following the steps required are reported.

First, a day per month has been chosen, as done in the previous case study. The reference year is from April 2018 to May 2019. Of course, the results will be conditioned to the solar production of that year, but it is consistent with the goal of this case study, finalized in understanding how a P2P with H_2 storage system could have affected the energy scenario in the reference year. It is worth noting that in July 2018 the PV production has been nil in the reference day considered in this study. Since it is expected that July is one of the most sunny months, the solar production of July 2017 has been considered in order to not undersize the system, since considering no PV production in all the July month would have been a too strong assumption. The energy produced in a day has been then discretized in 24 values (data are indeed available each 15 minutes) and the set of data resulting constitutes the input of the Matlab algorithm which compares production and consumption. The following figure 47 shows PV production for different months, hour by hour.

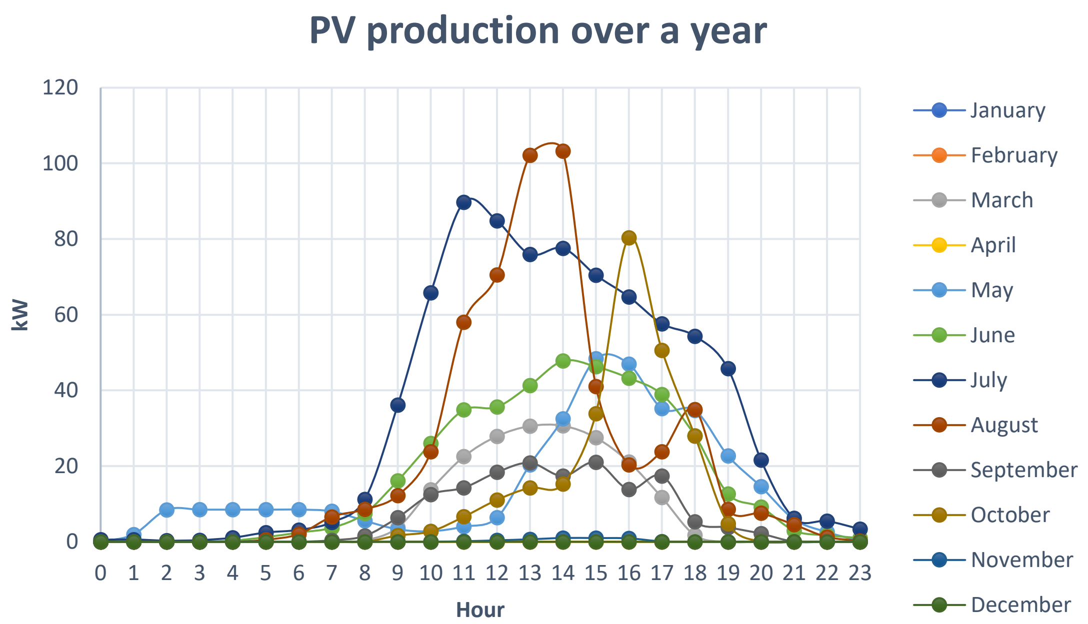


Figure 47 PV production

Load and PV production have hence been compared using the Matlab script described before, and surplus and deficit are obtained. They are shown hereafter in fig. 49, together with the comparison of consumption and RES production in fig. 48.

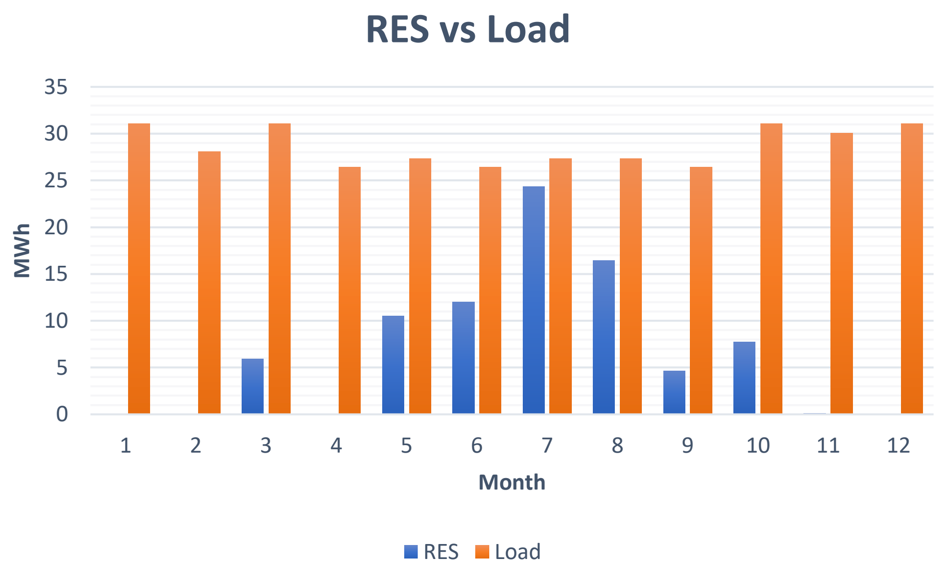


Figure 48 Comparison between load and PV production month by month

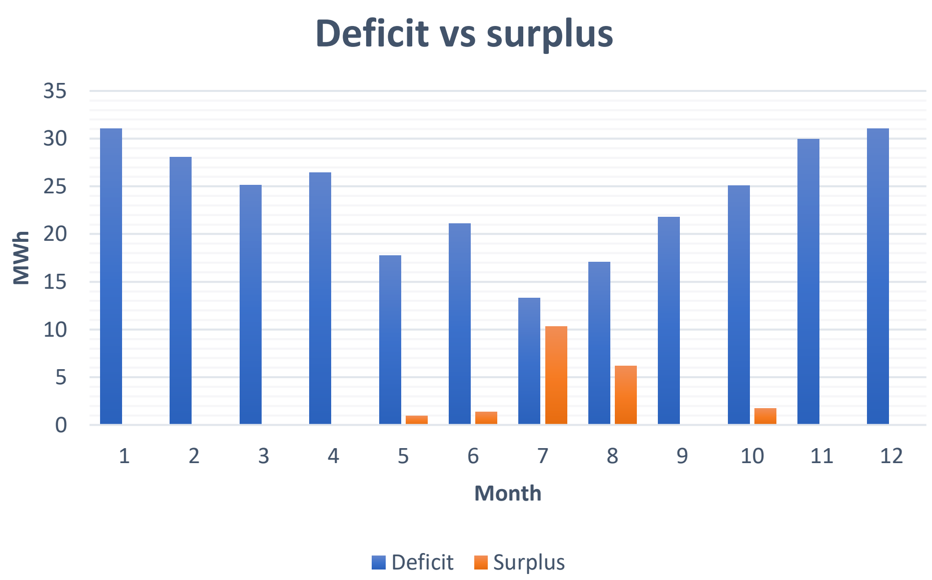


Figure 49 Energy deficit and surplus month by month

Observing the previous diagrams, it's clear how the current renewable system covers just a little part of the load, and a significant fraction of energy must come from external. RES production occurs during summer, mainly July, the only month when there is a significant surplus, even if lower than deficit. The load is quite flat, with peaks over 30 MWh in winter months.

Moving to the simulation, the appropriate code for the current system is the one that simulate control strategy 1. Indeed, in case of surplus energy charges the battery then is curtailed, while in case of deficit energy is supplied first from battery then from diesel generator. The following figure 50 shows the results in terms of usage of RES and load coverage.

TOTAL RES (MWh)	81.734
% LOAD	75%
% BATTERY	16%
% CURTAILED	9%

TOTAL LOAD (MWh)	343.648
% RES	18%
% BATTERY	3%
% EXT	78%

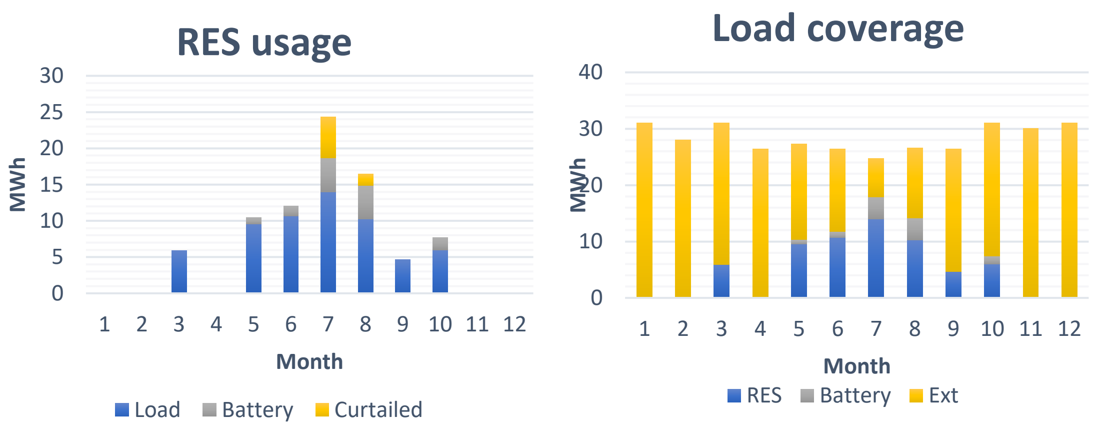


Figure 50 RES usage and load coverage

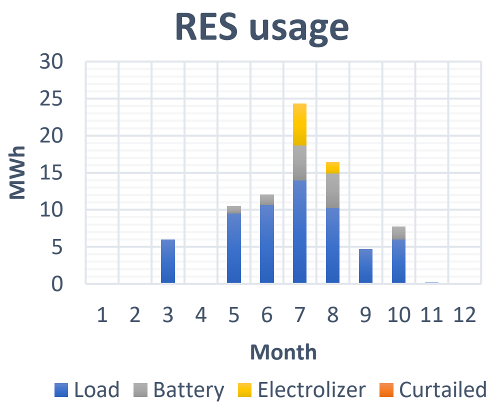
According to the simulation, 9% of RES is curtailed during the warmest months, as the histograms show, while energy is supplied almost totally by external source during the winter months. July is the month when the smallest part of external energy is required (9.42 MWh). On a yearly basis, 61 MWh are covered by RES and 11 MWh by battery (in total 21% of load). This data is reflected in [63], [67], where it is specified that around 20% of the load is covered by the hybrid renewable system (PV+battery). This is a great validation of the load model used and of the goodness of the Matlab code.

3.6 Proposed solution

The aim of this part is to see what would have changed if a solar/hydrogen/battery/diesel system have been used. This means to have a complete P2P system (strategy 3 in this work) instead of the current system. The system and the energy management are the same discussed earlier (Section 2). The size of the electrolyser and fuel cell have been chosen combining units of 25 kW (accordingly to the devices of REMOTE project). In this case study a nominal size of 75 kW (3 units) has been chosen for both. The size of hydrogen tank has been determined making sure that it becomes full at least for some hours in the period of maximum energy production. A reasonable choice is a tank of 5 kg. The simulation has been run and here the technical results are reported in fig. 51:

TOTAL RES (MWh)	81.734
% LOAD	75%
% BATTERY	16%
% ELECTROLIZER	9%
% CURTAILED	0%

TOTAL LOAD (MWh)	343.648
% RES	18%
% BATTERY	3%
% FC	1%
% EXT	78%



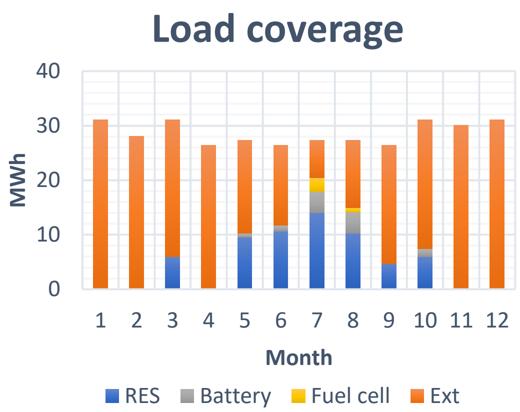


Figure 51 RES usage and load coverage

Comparing the above data with the current situation, it’s clear that by adding the hydrogen storage system very few changes in energy terms. Energy curtailment drops, while the summer surplus that cannot be stored in the battery is transformed in H_2 and used in the same months, the ones with lower external requirement. Only the economic analysis will allow to assess the feasibility of this scenario, but it is expected that considering the high cost of hydrogen devices and the low amount of energy recovered in H_2 storage (3.3 MWh, around 1% of load) the LCOE will be higher than current solution. In the next paragraph such study is carried on.

3.7 Economic analysis

The economic analysis has been led in conformity with what done for Paradise River case study (Section 2). For each scenario capital costs, operative costs and replacement costs have been calculated. Of course, the capital cost for the current solution is nil, since the system is already existent. The hypotheses on the costs of components and lifetime are the same of the previous case study, except for diesel price. For this case study community, the most recent diesel price is dated February 2019 and is equal to 1.77 CAD/l [63]. Such high price, higher than Paradise River one, can be justified noting the absence of year-round access road, while a winter road is the only way to reach the village, determining difficulties in transportation of fuel. The following figure 52 shows the costs evolution over the system lifetime comprehensive, as before, of NPV and unit costs. The column 'Current solution' refers to today scenario (hybrid PV/battery) while 'Proposed solution' indicates hybrid PV/hydrogen/battery system.

	PROPOSED SOLUTION							CURRENT SOLUTION					
year	capex	opex	replacement	tot cost	present cost	cumulative	Unit costs	opex (€)	replacemen	tot costs	present costs	cumulative	Unit costs
0	728,020.00 €			728,020.00 €	728,020.00 €	728,020.00 €				0.00 €	0.00 €	0.00 €	
1		118,733.76 €		118,733.76 €	116,691.66 €	844,711.66 €	2,491.77 €	115,063.98 €		115,063.98 €	113,084.99 €	113,084.99 €	333.58 €
2		118,733.76 €	63,000.00 €	181,733.76 €	175,536.24 €	1,020,247.90 €	1,504.79 €	115,063.98 €	63,000.00 €	178,063.98 €	171,991.60 €	285,076.59 €	420.47 €
3		118,733.76 €		118,733.76 €	112,712.22 €	1,132,960.11 €	1,114.02 €	115,063.98 €		115,063.98 €	109,228.54 €	394,305.12 €	387.71 €
4		118,733.76 €		118,733.76 €	110,773.68 €	1,243,733.79 €	917.21 €	115,063.98 €	63,000.00 €	178,063.98 €	166,126.30 €	560,431.42 €	413.30 €
5		118,733.76 €	438,000.00 €	556,733.76 €	510,476.17 €	1,754,209.96 €	1,034.93 €	115,063.98 €		115,063.98 €	105,503.60 €	665,935.03 €	392.88 €
6		118,733.76 €		118,733.76 €	106,996.05 €	1,861,206.00 €	915.05 €	115,063.98 €		115,063.98 €	103,689.04 €	769,624.07 €	378.38 €
7		118,733.76 €	63,000.00 €	181,733.76 €	160,951.38 €	2,022,157.38 €	852.15 €	115,063.98 €	63,000.00 €	178,063.98 €	157,701.25 €	927,325.32 €	390.78 €
8		118,733.76 €		118,733.76 €	103,347.24 €	2,125,504.63 €	783.74 €	115,063.98 €		115,063.98 €	100,153.02 €	1,027,478.34 €	378.86 €
9		118,733.76 €		118,733.76 €	101,569.77 €	2,227,074.40 €	729.95 €	115,063.98 €	63,000.00 €	178,063.98 €	152,323.29 €	1,179,801.62 €	386.69 €
10		118,733.76 €	473,000.00 €	591,733.76 €	497,487.50 €	2,724,561.90 €	803.71 €	115,063.98 €		115,063.98 €	96,737.57 €	1,276,539.20 €	376.56 €
11		118,733.76 €		118,733.76 €	98,106.02 €	2,822,667.91 €	756.95 €	115,063.98 €		115,063.98 €	95,073.78 €	1,371,612.98 €	367.82 €
12		118,733.76 €	63,000.00 €	181,733.76 €	147,578.34 €	2,970,246.25 €	730.15 €	115,063.98 €	63,000.00 €	178,063.98 €	144,598.25 €	1,516,211.24 €	372.72 €
13		118,733.76 €		118,733.76 €	94,760.38 €	3,065,006.63 €	695.49 €	115,063.98 €		115,063.98 €	91,831.56 €	1,608,042.79 €	364.88 €
14		118,733.76 €		118,733.76 €	93,130.60 €	3,158,137.23 €	665.43 €	115,063.98 €	63,000.00 €	178,063.98 €	139,667.13 €	1,747,709.92 €	368.25 €
15		118,733.76 €	438,000.00 €	556,733.76 €	429,171.91 €	3,587,309.14 €	705.47 €	115,063.98 €		115,063.98 €	88,699.90 €	1,836,409.82 €	361.14 €
16		118,733.76 €		118,733.76 €	89,954.64 €	3,677,263.78 €	677.96 €	115,063.98 €		115,063.98 €	87,174.34 €	1,923,584.16 €	354.64 €
17		118,733.76 €	63,000.00 €	181,733.76 €	135,316.43 €	3,812,580.20 €	661.56 €	115,063.98 €	63,000.00 €	178,063.98 €	132,583.95 €	2,056,168.12 €	356.79 €
18		118,733.76 €		118,733.76 €	86,886.98 €	3,899,467.19 €	639.05 €	115,063.98 €		115,063.98 €	84,201.50 €	2,140,369.62 €	350.77 €
19		118,733.76 €		118,733.76 €	85,392.61 €	3,984,859.80 €	618.67 €	115,063.98 €	63,000.00 €	178,063.98 €	128,062.54 €	2,268,432.16 €	352.19 €
20		118,733.76 €	744,780.00 €	863,513.76 €	610,352.75 €	4,595,212.55 €	677.76 €	115,063.98 €		115,063.98 €	81,330.05 €	2,349,762.21 €	346.57 €
21		118,733.76 €		118,733.76 €	82,480.53 €	4,677,693.08 €	657.07 €	115,063.98 €		115,063.98 €	79,931.25 €	2,429,693.46 €	341.30 €
22		118,733.76 €	63,000.00 €	181,733.76 €	124,073.33 €	4,801,766.41 €	643.84 €	115,063.98 €	63,000.00 €	178,063.98 €	121,567.89 €	2,551,261.35 €	342.08 €
23		118,733.76 €		118,733.76 €	79,667.76 €	4,881,434.18 €	626.07 €	115,063.98 €		115,063.98 €	77,205.42 €	2,628,466.76 €	337.11 €
24		118,733.76 €	63,000.00 €	181,733.76 €	119,842.15 €	5,001,276.33 €	614.71 €	115,063.98 €	63,000.00 €	178,063.98 €	117,422.15 €	2,745,888.91 €	337.50 €
25		118,733.76 €	375,000.00 €	493,733.76 €	319,987.03 €	5,321,263.36 €	627.88 €	115,063.98 €		115,063.98 €	74,572.54 €	2,820,461.45 €	332.80 €
26		118,733.76 €		118,733.76 €	75,627.44 €	5,396,890.80 €	612.31 €	115,063.98 €	63,000.00 €	178,063.98 €	113,417.80 €	2,933,879.25 €	332.87 €
27		118,733.76 €	63,000.00 €	181,733.76 €	113,764.39 €	5,510,655.19 €	602.06 €	115,063.98 €		115,063.98 €	72,029.45 €	3,005,908.70 €	328.41 €
28		118,733.76 €		118,733.76 €	73,048.37 €	5,583,703.56 €	588.25 €	115,063.98 €	63,000.00 €	178,063.98 €	109,550.00 €	3,115,458.69 €	328.22 €
29		118,733.76 €		118,733.76 €	71,792.01 €	5,655,495.57 €	575.27 €	115,063.98 €		115,063.98 €	69,573.08 €	3,185,031.78 €	323.98 €
30		118,733.76 €	473,000.00 €	591,733.76 €	351,636.39 €	6,007,131.96 €	590.67 €	115,063.98 €	63,000.00 €	178,063.98 €	105,814.10 €	3,290,845.87 €	323.58 €

Figure 52 Cash flow

What changes, besides the presence of capital costs for the proposed solution, is the addition of hydrogen chain components operative costs. Although the proposed solution allows lower diesel consumption due to less working hours (62 less) and less fossil kWh needed (3341 less), the operative costs of the proposed solution are anyway higher than current solution, because of the introduction of new devices. Concerning replacement costs, in proposed solution it will be necessary to replace diesel generator just one time less. The cost trends are reported in the following chart:

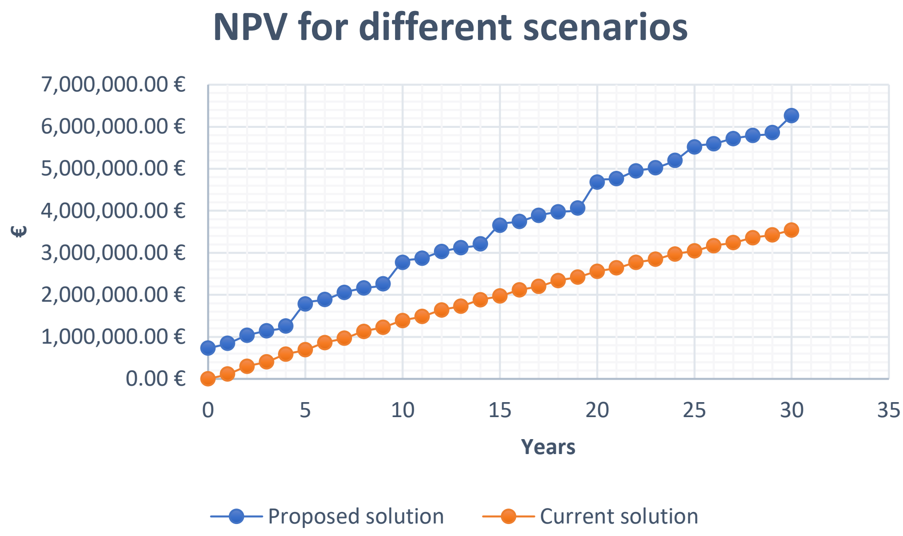


Figure 53 Cost trend

Table 8 LCOE for current and proposed solution

	Current solution	**Proposed solution**
RES prod (MWh)	81.734	81.734
LCOE (€/kWh)	0.414	0.733

The diagram confirms the expectations made in the previous paragraph, assessing the unfeasibility of such proposed solution, in fact the LCOE for current solution results to be 0.414 €/kWh while for proposed solution 0.733 €/kWh (tab. 8). This could be explained observing again the solar production and the plot showing energy surplus and deficit in the previous paragraph (figs. 48 and 49). Except for May to October period, the external source represents practically the only way to provide power. Now, battery can cover 3% of the load, mostly in August and September. Adding an additional storage system could be useful to reduce the energy surplus which take place in July and August, but the rest of the year remains devoid of renewable energy to exploit. Considering the high cost of hydrogen technologies, such small technical advantage (3.3 MWh provided by H_2) will be, of course, not a good economic choice.

This means that to justify in appropriate way the introduction of hydrogen storage system, higher energy surplus should be available. To validate this statement, in the next paragraph new scenarios are studied whereas additional renewable sources are installed. Specifically, wind turbines are added to the solar system already existent, and a sensitivity analysis on wind farm size is carried out. While the other parts of the system don't change, variation of LCOE will be studied.

3.8 Proposed solution 2

To validate the hypothesis just made, an increasing number of wind turbines will be added to the already present system to see what effects they produce. The wind distribution, computed as in former case study, is shown in figure 54.

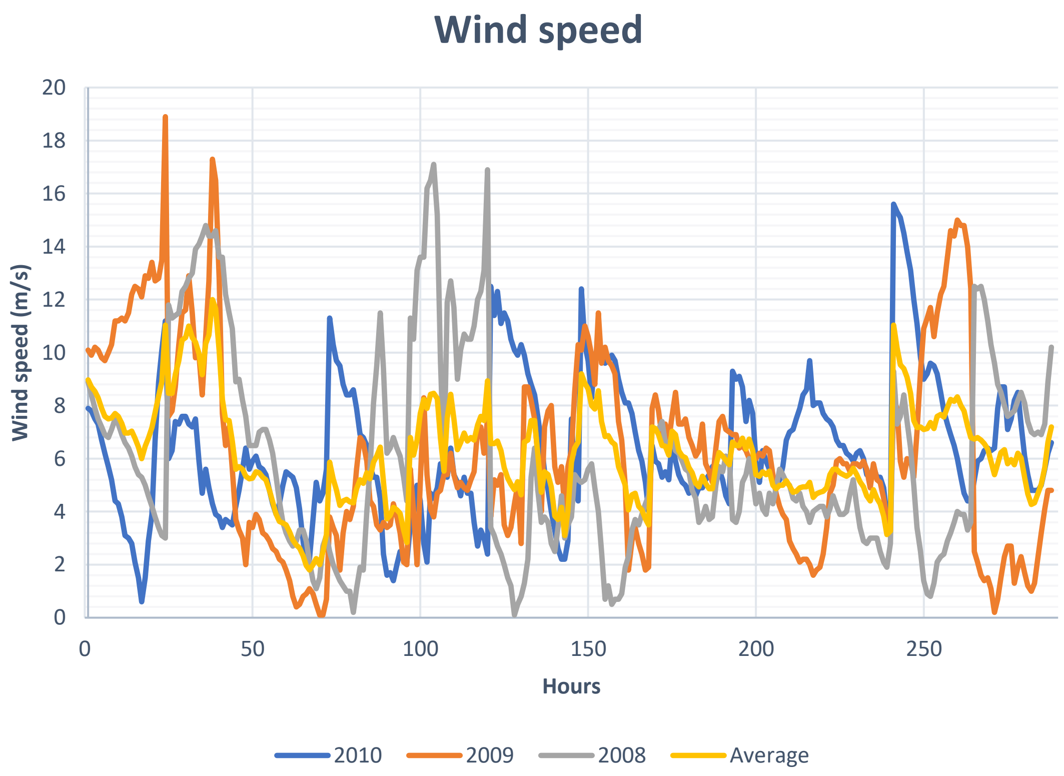


Figure 54 Wind speed in Colville Lake

The wind turbine model is Bergey Excel 10, the same considered for the previous case study. The installation of two wind turbines is first considered. The total RES installed will be 156 kW (136 kW from PV and 20 kW from wind energy). The simulation is run and the outcomes are shown in the following figures 55:

TOT RES (MWh)	117.792
% LOAD	80%
% BATTERY	12%
% ELECTROLIZER	7%
% CURT	1%

TOT Load (MWh)	343.648
% RES	28%
% BATTERY	4%
% FC	1%
% EXT	68%

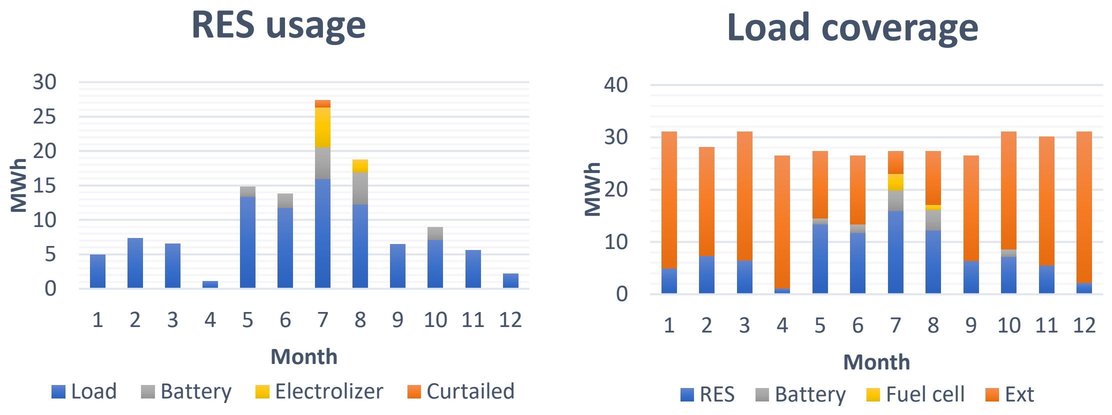


Figura 55 RES usage and load coverage

To understand better the effects of wind turbines, the configuration with 3 turbines (30 kW of wind energy) is also presented:

TOT RES (MWh)	135.822
% LOAD	82%
% BATTERY	11%
% ELECTROLIZER	6%
% CURT	1%

TOT Load (MWh)	343.6477
% RES	32%
% BATTERY	4%
% FC	1%
% EXT	63%

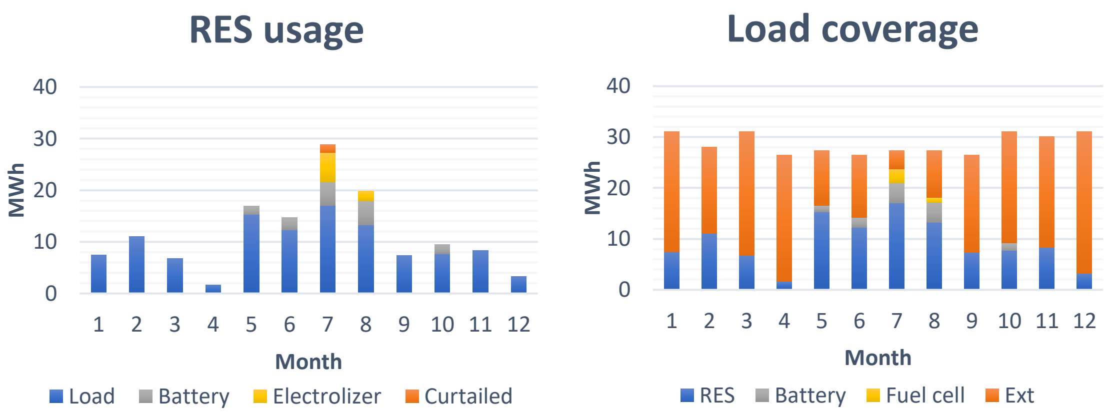


Figure 56 RES usage and load coverage

Comparing figs. 51, 55, 56, it is noted that the impact of the wind energy is almost exclusively on the share of load covered by RES (75% with no wind turbines, 80% with two, 82% with three): the additional renewable energies according to local wind distribution (high in the first months and during fall) cover directly the load (high right in that months), affecting very few the storage systems (just 12 kg_{H2} produced more). This can be explained recognising that the surplus doesn't increase significantly, as show the comparison in fig. 57. Of course the external requirement decreases (from 78% to 68% to 63%), but on the other hand a little curtailment occurs in July (around 1% of the RES production).

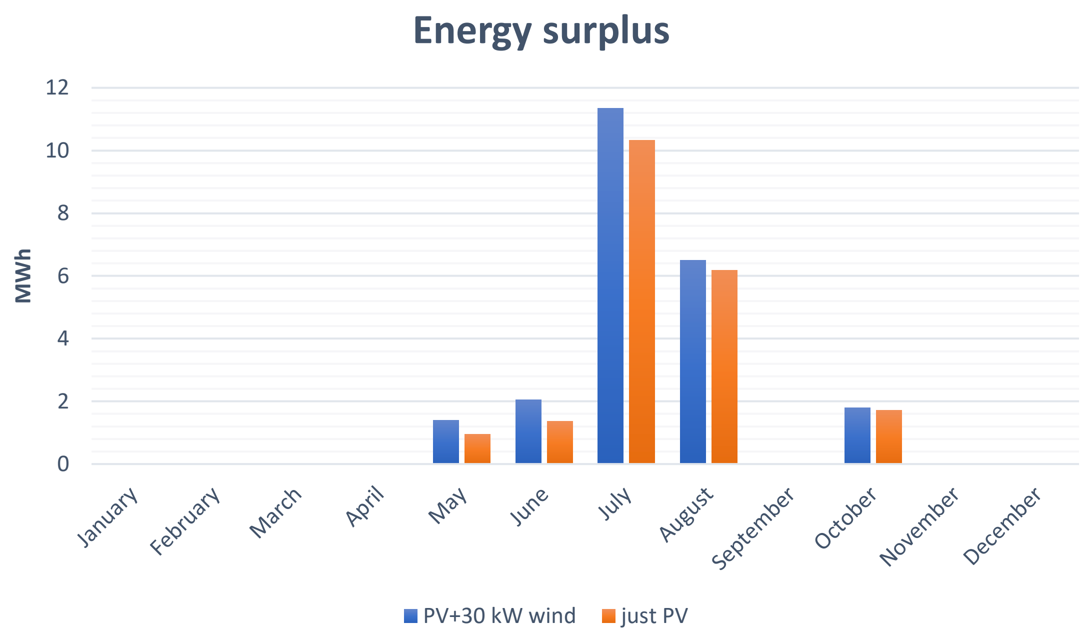


Figure 57 Comparison between energy surplus with and without 3 wind turbines. It is noticed that the surplus increases a bit just in the months when it already occurred, because in the other months the energy added cover directly the load, which is the priority in the control strategy used

The cost trend deriving from the economic analysis lead to the following situation (fig. 58):

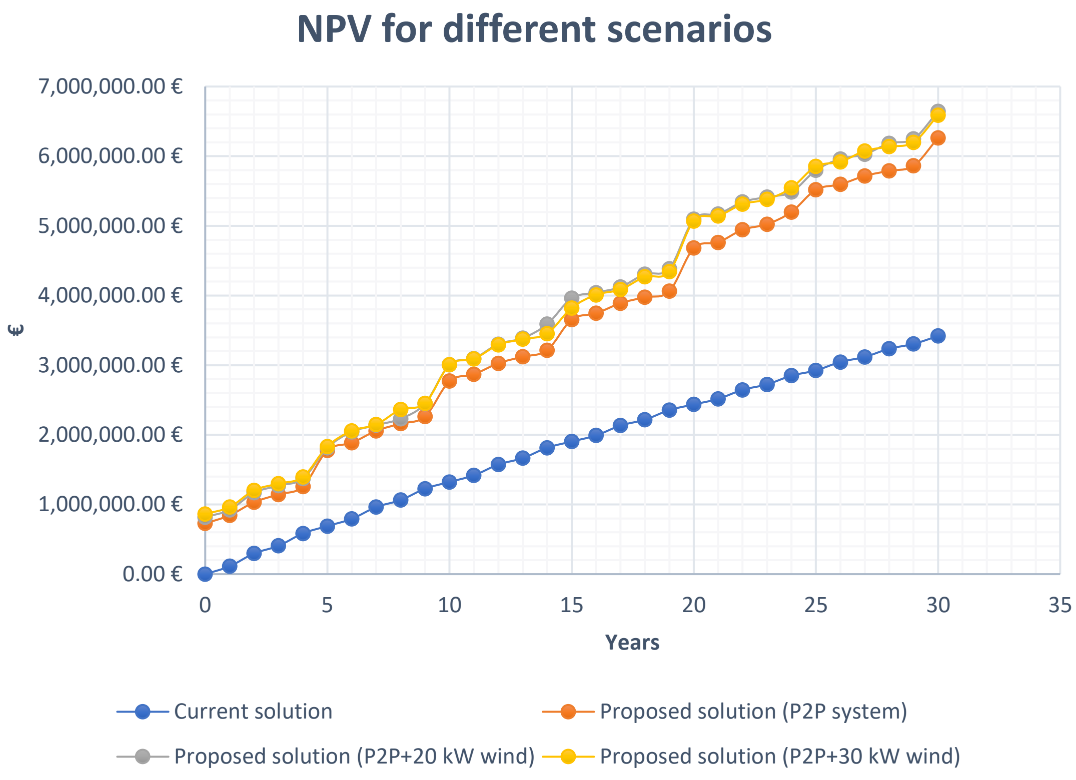


Figura 58 Cost trend

Table 9 LCOE for current and two proposed solutions

	Just PV	PV+20 kW wind	PV+30 kW wind
RES prod (MWh)	81.734	117.793	135.822
LCOE (€/kWh)	0.733	0.810	0.804

In the previous paragraph 3.7 it is explained why moving from the current system to a P2P with hydrogen system is cost effective. The plot in fig.58 shows that adding wind turbines (more RES generation) the total costs over the long period doesn't change significantly (in face of an higher initial capital cost). Of course, the different RES production affects the LCOEs, which is 0.810 €/kWh for the proposed solution with 20 kW of wind energy and slightly lower for the case with 30 kW of wind energy, that is 0.804 €/kWh (tab. 9). The trend is decreasing, even if they are higher than the case with no turbines (0.733 €/kWh). This is because the goal to increase the surplus affects only the months when there is already PV surplus, keeping the other months in high energy deficit (fig. 57). Thus, the goal is achieved only partially. In fact, if on a side the RES added reduce diesel necessity, on the other side it doesn't affect storage, not involving additional energy flows to electrolyser to produce hydrogen to store. To extend surplus to other months, more turbines will be installed in the next paragraph.

3.9 Sensitivity analysis on wind farm size

Once understood the outcomes of the previous paragraph, the natural step forward is to see what happens increasing wind energy, in order to seek an optimal wind farm size and have the lowest LCOE. Thus, the analysis and calculations of previous paragraphs are repeated for 130 kW, 140 kW, 150 kW of wind energy (that is 13, 14, 15 turbines model Bergey Excel 10 in the wind farm).

The following figure 59 shows the LCOE of the different scenarios:

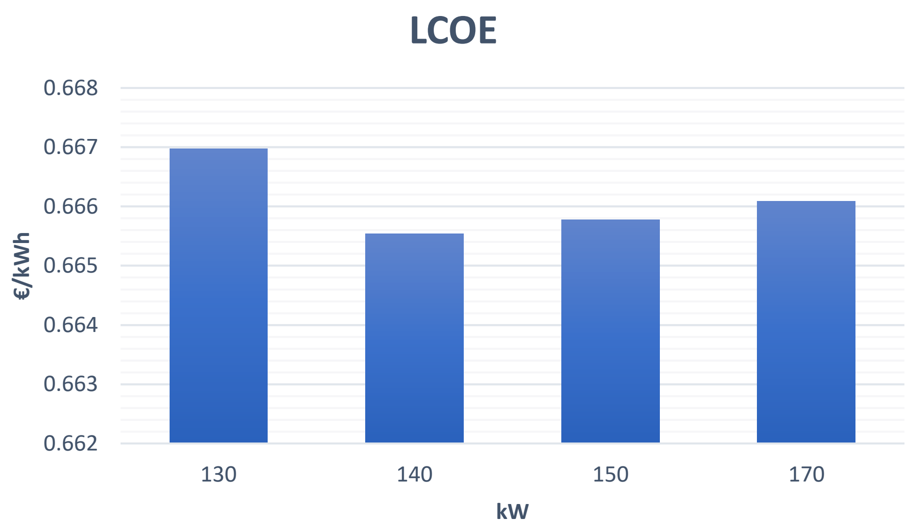


Figure 59 LCOE for different wind farm size

The best LCOE is found for 140 kW of wind energy. The meaning of the minimum value is that increasing wind energy the surplus increases, reducing the use of diesel with the benefit of direct renewable usage and storage. The reduction of operative and replacement costs due to the reduced use of diesel power prevails over the initial costs of the wind turbines. Adding turbines, at a certain point capex due to the installation of new turbines prevail, and the LCOE starts to increase again. These are the technical details of such optimal configuration:

TOT RES (MWh)	333.949
% LOAD	67%
% BATTERY	11%
% ELECTROLIZER	7%
% CURT	15%

TOT Load (MWh)	343.648
% RES	65%
% BATTERY	9%
% FC	3%
% EXT	22%

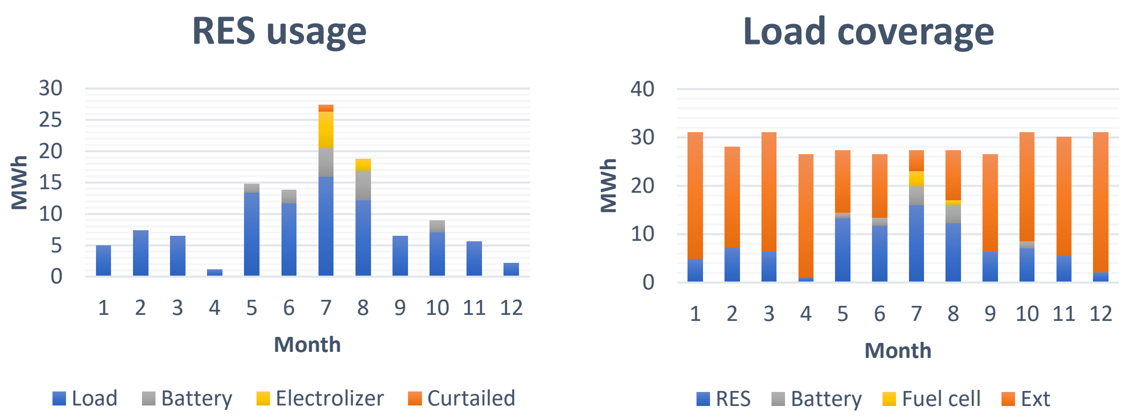


Figure 60 RES usage and load coverage

The issues of distribution of energy surplus highlighted at the end of previous paragraph is eventually solved, as shows the next figure 61.

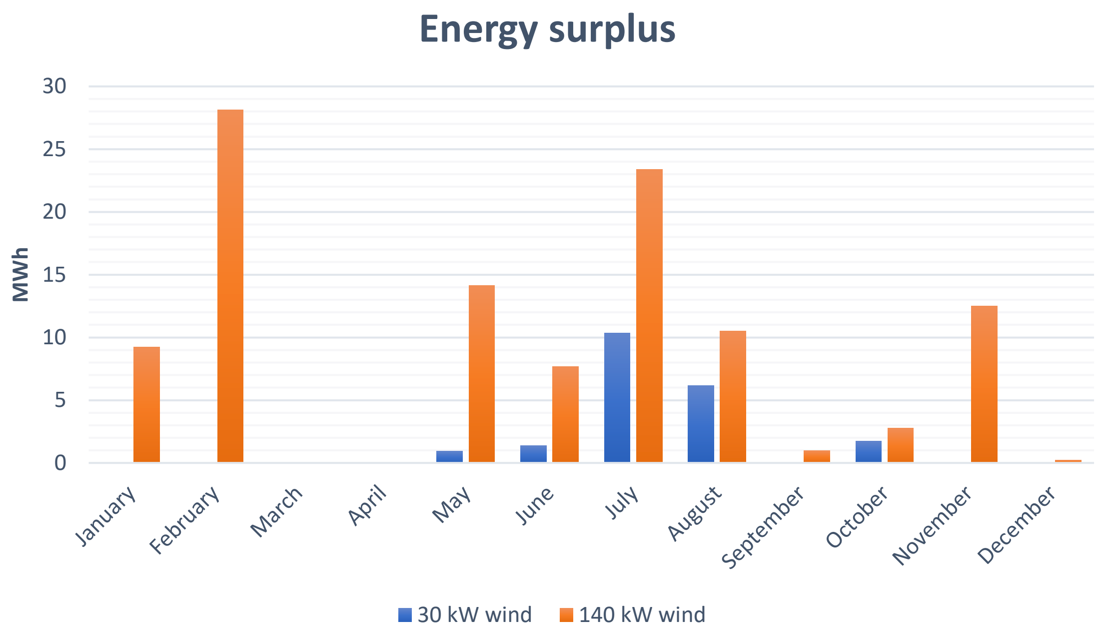


Figure 61 Comparison between energy surplus with 3 and 14 wind turbines. In the latter case RES production is enough to generate surplus even in months with high load.

Differently from the comparison between no wind and 30 kW wind, energy surplus is not only higher but also better distributed along the year. This allows a better exploitation of storage (+6% of load covered by stored energy). The highest surplus months are February, when the wind speed is the highest, and July, when PV gives its best contribute.

The lowest LCOE is found for a wind farm with 14 turbines, that is 140 kW of wind power in addition of 136 kW of PV power. It is 0.6655 €/kWh. Together with a better storage exploitation and a reduction of external requirement, however, wind power addition determines energy curtailed increasing up to 15% (fig. 60). Finally, concerning LCOE, it can be noticed that different LCOEs of fig. 59 change slightly (3rd decimal digit). As a consequence, the configuration with 170 kW could be considered the best solution because in the face of an increase of 0.001 €/kWh of LCOE, the energy required from external drops from 22% to 19% of the load, with associated environmental benefits.

3.10 Outlook for next years

Similar to Paradise River case study, a prediction over next years is made to see LCOE evolution. Considerations and assumptions made on components prices for the analysis are the same of previous case study (Section 2) except for the diesel price, which is calculated to be +52% with respect to Canadian average. The following figure 62 shows LCOEs predicted in 2025 and 2030, both for the current and the best proposed solution individuated in previous paragraphs.

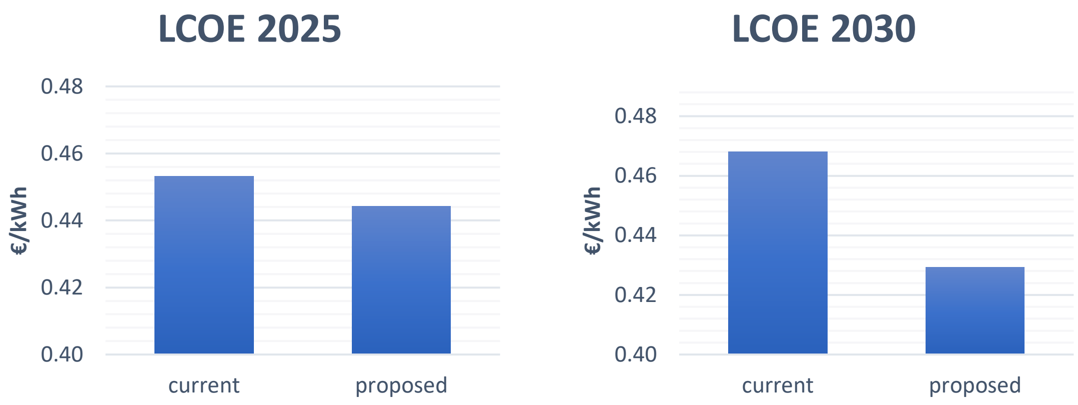


Figure 62 LCOE prediction in 2025 and 2030

Current solution (solar/battery system) foresees a slightly increasing trend over time, due to the increasing diesel price. Proposed solution (sola/hydrogen/battery system) envisages a significant reduction in 2025, while in 2030 the reduction is less sharp. In 2025 LCOEs for the two scenarios are very close, while in 2030 it is expected to be lower of 0.039 €/kWh in favour of proposed solution.

Section 4 – Environmental analysis

4.1 Methodology description

The criteria adopted so far to choose among different configurations don't consider the environmental aspect directly, rather no discriminant is used among scenarios on the basis of pollutant emissions. In this paragraph the most environmentally friendly scenario will be individuated and avoided emissions will be estimated for the two case studies. Clearly, the best scenario under the environmental point of view is the one minimizing the use of diesel generators. In this analysis, in fact, just operational emissions and not the ones deriving from equipment production are considered. A more detailed model should include life-cycle emission factors and sustainability indicators, as in [11]. Diesel engines release many hazardous pollutants, including CO_2, CO, SO_2, NO_x, particulate matter.

The calculation of CO_2 emissions is based on the amount of fuel consumption by diesel generator. Depending on diesel properties, the carbon content may change and consequently CO_2 emissions. The amount of carbon dioxide produced per liter of fuel burnt is usually around 2.7 kg/l, but a value ranging between 2.4 and 3.5 kg/l can be found in literature. To be precautionary, an emission factor of 3.0 kg/l is adopted in the current analysis [19].

Other pollutants footprint is based on the emission factor methodology provided by National Pollutant Release Inventory (NPRI) section of Canada government website [68]. The model is worth for diesel fuel generators up to 600 hp and assumes uncontrolled emissions. For each substance, an emission factor expressed in kg/m^3 is provided. Multiplying this data by the amount of diesel burned, the actual emission is found.

For both cases study, the outcomes generally subvert the LCOE analysis results. In the latter, in fact, the best option (RES+battery) is also the one which envisages less coverage of the load by RES. The former, instead, privileges the solution covering the highest part of load without using external (fossil) resources, that is RES+battery+H_2.

4.2 Outcomes

For Paradise River, wind-only is the configuration which maximize the load coverage by RES. Scenario 3, that is the combined storage, leads to just 3% of load covered by diesel (corresponding to 5590.8 kWh/year). Using an annual fuel consumption of 79865 litres/year and an annual fossil fuel generation of 210 MWh/year [69], the specific consumption (l/MWh) is calculated as:

$$79865\,\frac{l}{year} \div 210\,\frac{MWh}{year} = 380.31\,\frac{l}{MWh}$$

that means, using previous assumption:

$$3.0\,\frac{kg_{CO_2}}{l} \times 380.31\,\frac{l}{MWh} = 1140.93\,\frac{kg_{CO_2}}{MWh}$$

being the emission deriving from the production of 1 MWh of power using diesel generator. To calculate total emissions per year:

$$5590.8\,\frac{kWh}{y} \times 1.14\,\frac{kg_{CO_2}}{kWh} = 6378.71\,\frac{kg_{CO_2}}{y}$$

Namely, around 6.3 tons of CO_2 are released in the atmosphere each year. It is the most environmentally friend scenario for Paradise River case study.

Keeping the same amount of diesel fuel consumed, other air contaminants have the following footprint:

Table 10

Substance Name	Emission Factor	EF Units	Total Release	Units
Carbon Monoxide (CO)	15.595	kg/m^3	**1.246**	tonnes
Sulphur Dioxide (SO_2)	4.761	kg/m^3	**0.380**	tonnes
Oxides of Nitrogen, expressed as NO_2 (NO_x)	72.396	kg/m^3	**5.782**	tonnes
Volatile Organic Compounds (VOCs)	5.910	kg/m^3	**0.472**	tonnes
Total Particulate Matter (TPM)	5.089	kg/m^3	**0.406**	tonnes
Particulate Matter less than or equal to 10 µm (PM10)	5.089	kg/m^3	**0.406**	tonnes
Particulate Matter less than or equal to 2.5 µm (PM2.5)	5.089	kg/m^3	**0.406**	tonnes

For Colville lake, proposed solution involving both solar PV and wind turbines leads to a configuration where 22% of load is supplied from diesel generators (77.3 MWh/year). Carrying out calculations as before, considering an annual fuel consumption of 202264 litres/y and an annual fossil fuel generation of 627 MWh [69], a specific consumption of 344.59 l/MWh is obtained. The amount of carbon dioxide emitted is 79910.42 kg_{CO2} per year. The summary for other pollutants breakdown is displayed in tab. 11.

Table 11

Substance Name	**Emission Factor**	**EF Unit**	**Total Release**	**Units**
Carbon Monoxide (CO)	15.595	kg/m^3	**3.154**	tonnes
Sulphur Dioxide (SO2)	4.761	kg/m^3	**0.963**	tonnes
Oxides of Nitrogen, expressed as NO2 (NOx)	72.396	kg/m^3	**14.643**	tonnes
Volatile Organic Compounds (VOCs)	5.910	kg/m^3	**1.195**	tonnes
Total Particulate Matter (TPM)	5.089	kg/m^3	**1.029**	tonnes
Particulate Matter less than or equal to 10 μm (PM10)	5.089	kg/m^3	**1.029**	tonnes
Particulate Matter less than or equal to 2.5 μm (PM2.5)	5.089	kg/m^3	**1.029**	tonnes

Pollutant emissions, calculated for the most environmentally friendly scenario, will be compared to current diesel based system in Section 5 of this work, in order to see emissions avoided in different configurations.

4.3 Carbon tax framework

Carbon tax, that is a pricing per each tonne of carbon dioxide emitted from burning carbon-based fuels, is in the agenda of the Canada government, at the heart of 2019 federal electoral campaign. Some provinces (e.g. British Columbia, Alberta) have their own carbon pricing plan, others received a federally mandated carbon tax imposed on them. Newfoundland and Labrador (NL) and Northwest Territories (NWT) came up their own carbon pricing plans by the federal deadline. The first, where Paradise River is, came into effect on January 1, 2019. Such carbon tax foresees exemption for off-grid diesel electricity generation [70]. Paradise River will be thus not affected by carbon tax. Northwest Territories carbon tax became effective September 1, 2019. No exemption for off-grid communities is explicated on province website – even if the new approach is at the beginning when this text has been drafted. The new NWT Carbon tax will reflect CAD 20/tonne of GHG emissions at the beginning. To pursue this goal, a differentiate tax for the various types of fuel is adopted. Non-motive diesel will be taxed 0.055 CAD/l [71], which could be applied to Colville Lake community. Following the calculations[5], LCOE for current configuration should increase from 0.432 €/kWh to 0.442 €/kWh, that is just +0.1 €/kWh. Clearly such value doesn't affect significantly the economic scenario because of such small fossil fuel generation. Even if carbon tax is expected to increase already from next year till 50 CAD per tonne in 2022, the process must occur gradually and is not supposed to change deeply and shortly the scenarios presented in this work.

[5] $268.81\,\frac{MWh}{y} \times 344.59\,\frac{l}{MWh} \times 0.038\,\frac{€}{l} = 3509.89\,\frac{€}{y}$ of taxes

Section 5 – Discussion of results and comparisons

5.1 Governance, funding and regulatory aspects

In Canada each province and territory have its own legislation governing electricity production, transmission and pricing, and the nature of regulations differs substantially across them. This makes impossible to develop general consideration for all the Country remote communities. There are appropriate bodies which oversee and enforce electricity system, and several utilities take care of generate and distribute electricity. More than 100 remote communities obtain electricity from small service providers that are not established utilities [72]. This means that the service providers of many remote communities may have little capacity to effect change in their community's electricity system. Another important aspect surrounding electricity systems in remote communities is subsidization of electricity rates. This occurs in many communities because of high generation cost, in ways varying across regions. Usually provinces subsidize electricity in off-grid communities for a limited amount of consumption, in order to make the price more similar to in-grid communities. The projects presented in this work and others aimed to power shift in remote communities (or more generally to improve electricity system) depends strongly on financial aid by government and other active players. Being many of service providers small, with a little capacity to fund expensive energy projects, improvements to electricity systems of remote communities are limited by funding. There are several federal and provincial funding programs across the Country available to remote communities. The economic aspect is crucial, but not the only point. Not always easy relationships between government and indigenous people that often live in remote communities is a barrier to overcome. Governments should shift their policies with Indigenous communities as a part of their commitments to reconciliation. Government and Indigenous bodies should work collaboratively to develop energy targets and strategies for enabling the transition to clean energy. Funding and financing for clean energy projects in remote Indigenous communities should be provided to subjects demonstrating partnership and engagement with communities. Financial supported projects should guarantee power rates that avoid recurring costs of diesel generator equipment. In long-term target, such projects should include health, environmental and social cost savings. As far as authorization is concerned, the installation of a H_2-based stand alone plant requires the observance to territorial and national regulations (pressurized hydrogen tank, electrical equipment, preservation of wildlife) and has to follow a permitting process aimed to the approval of different parts of the systems and phases of installation, from commissioning to operation. An example of this process can be found in [73].

5.2 A comparison with other Canadian case studies

LCOEs obtained will be now compared with the ones from some other similar Canadian case studies, since their calculation is strongly dependent on the Country[6] other than on the assumptions made. Concerning RES+battery cases, LCOEs found are consistent with the work of Rahman et al. [28]. The study considers seven scenarios with different renewable penetration for the off-grid community of Sandy Lake, Ontario. The LCOE of the RES+battery+diesel hybrid system is comparable with the ones of the present study (range between 0.36 €/kWh, with 0% of renewables, and 1.48 €/kWh, with 100% of renewables). Hydrogen storage is not considered in this study.

Bhattarai et al. in [30] analyse the performance of a wind-diesel hybrid system to replace the existing diesel generating system in the off-grid community of Brochet, Manitoba. The levelized cost of energy of the optimized system is 0.64 €/kWh, around 0.3 €/kWh more than Paradise River corresponding scenario. The mentioned paper, however, is dated 2015 – wind turbines cost evidently weighs.

Khan et al. [29] carried out a pre-feasibility study of a hybrid energy system to supply energy to a remote off grid house in St. Johnn, Newfoundland. Among the different configurations, wind/diesel/battery is the best stand-alone system with a LCOE of 0.47 €/kWh. The integration of fuel cells into the system reveals to be not feasible, with LCOE well higher than 1 €/kWh. The use of PV/battery system is also cost effective, having a LCOE in the range 0.9÷1 €/kWh. This is not surprising, since the paper dates back to several years ago. Diesel/battery system, finally, leads to 0.9 €/kWh.

[6] The interest rate depends in fact on the Country, as well as cost of diesel and components costs.

Generally, the LCOEs resulting in the current work are in conformity with the above mentioned studies, above all considering that each work uses even different assumptions and methodologies.

5.3 A comparison with European demo projects

REMOTE is an EU project, which aim is to “demonstrate the technical and economic feasibility of fuel cells-based H_2 energy storage solutions in isolated and off-grid remote areas” [74]. Four demo solutions, with supply by renewable energy sources (RES), will be installed in either isolated micro-grids or off-grid remote areas: at Ginostra (South Italy), Agkistro (Greece), Ambornetti (North Italy) and Froan Islands (Norway). These demos comprise two different plant architectures, an integrated P2P system and a non-integrated power-to-gas and gas-to-power (P2G+G2P) system, with different loads to be covered and different types of RES available on-site. In this paragraph a comparison of Paradise River case study with Ginostra and Ambornetti demos will be carried out, since they are characterized by residential loads, as the case studies analysed in this work. Moreover, they have the same architecture modelled for Paradise River and Colville Lake and share the same control strategy in terms of priority of energy flows.

Ginostra (South Italy) is an off-grid island village, characterized by an increase in energy demand and population during summer months. To reduce diesel consumption, a proposed solution including Li-Ion battery, solar PV and hydrogen storage is implemented in a P2P system. The following figure 63 compares the load and the PV production for Ginostra and Paradise River.

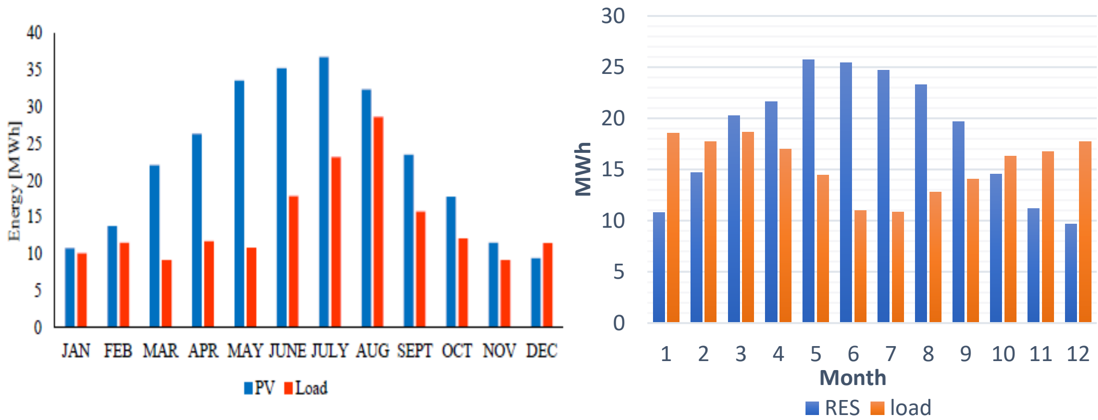


Figure 63 Load and PV production for Ginostra (left) and Paradise River (right)

Ginostra load (left) presents peaks in summer months (tourism) while in Paradise River it is flatter and more accentuated during winter. RES production both in Ginostra and in Paradise River is higher during summer, as it is solar PV and both localities are in the northern hemisphere. In Ginostra there are 5 months where production is significantly higher than load, while in the other months they are comparable. In Paradise River there are 6 months with great displacement, and two with sharp predominance of load. In this case the surplus stored during fall is exploited in December and January. In Ginostra higher part of PV production in excess during consecutive months (from March to July) is curtailed, as confirm the table showing the results of the simulation (tabs. 12 and 13). The higher amount of energy going to electrolyser to produce hydrogen (+13.3%) and of load covered by energy produced by fuel cell (+6%) in Paradise River is also due to bigger devices size. The higher share of load covered by battery (+9.1%) in Ginostra can be explained considering the significantly smaller hydrogen tank size. When deficit periods occur, in fact, in REMOTE case study hydrogen tank gets empty quickly, stressing promptly the battery.

Table 12

	Ginostra	**Paradise River**
Load covered by RES	47.8%	48.0%
Load covered by fuel cell	3.5%	9.5%
Load covered by battery	44.3%	35.2%
Load covered by external source	4.4%	7.3%

Table 13

	Ginostra	**Paradise River**
RES to load	31.4%	40.4%
RES to electrolyzer	7.9%	21.2%
RES to battery	32.2%	35.7%
RES curtailed	28.5%	2.8%

The following figure 64 compares instead hydrogen state of charge over the year for the two case studies.

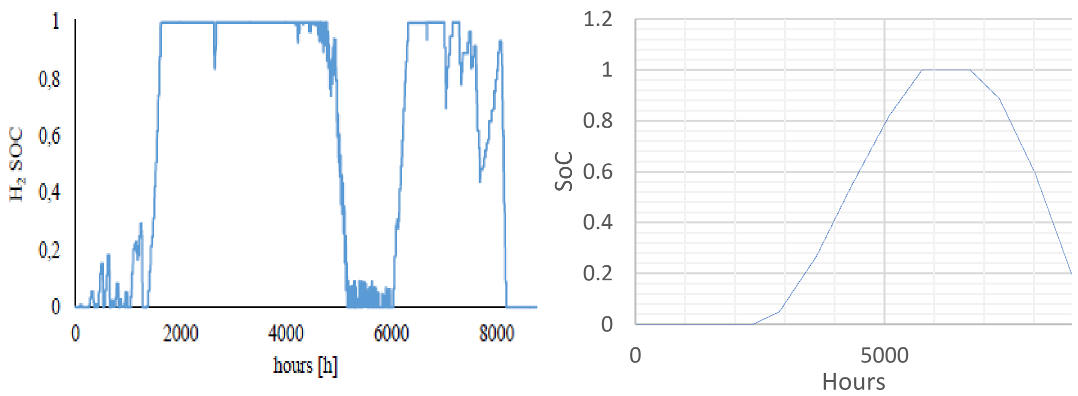


Figura 64 Hydrogen SoC in Ginostra (left) and Paradise River (right)

In Ginostra case (left figure) the tank is filled at the beginning of the year thanks to the high amount of spring RES (when it is also curtailed). This process occurs much slower in Paradise River (for instance, at 2000 h the tank is practically full in the former, it's starting to charge in the latter). For Ginostra case hydrogen SoC is sharply reduced in the summer, when the load reach peaks. In Paradise river that is right the period (5000÷6000 h) when there is maximum discrepancy between load and RES production in favour of the latter, so the tank gets full. In Ginostra a better exploitation of local RES could be achieved by increasing the size of hydrogen tank, which is not possible because of lack of space available in the area [46]. The different shape of the curves is evidently due to very different tank sizes used in the two studies.

To reduce the amount of energy curtailed in Paradise River a mix RES generation (PV+wind) has proven to be more suitable, leading to the following production/load scenario.

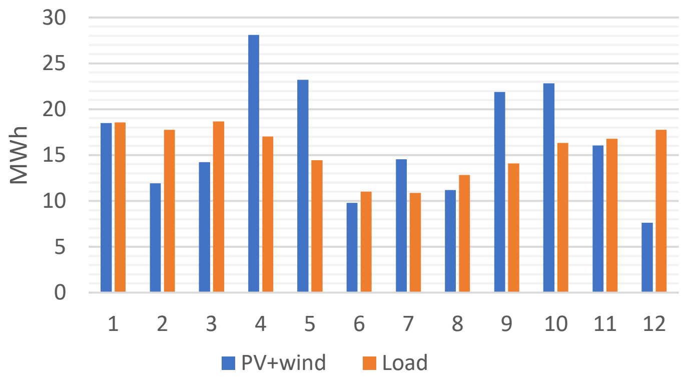


Figure 65 Load and RES production in Paradise River when PV+wind are used as energy sources

Comparing figures 65 and 63, referred to PV-only, what comes up is that the profile is strongly affected by wind distribution (wind energy contributes for 75% in generation mix). In this way, less surplus is produced during summer (which leads to less curtailment) and the high amount of energy available during fall is stored and exploited during the winter. The details of this scenario have been discussed in Section 2.

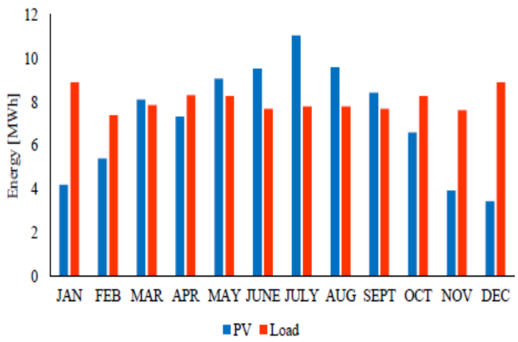
The following table 14 compares the current and proposed solutions for the two case studies.

Table 14

	Ginostra	**Paradise River**
Current solution	3x48 kW + 160 kW diesel gen	150 kW diesel generator
RES	170 kW PV	45 kW PV+30 kW wind
P2P	50 kW electrolyser 50 kW fuel cell	80 kW electrolyser 70 kW fuel cell
Storage	600 kWh battery+22m^3 H2	1400 kWh battery+600 kg H2
NPV after 30 years	2,188,679 € current solution 1,934,885 € proposed solution	2,084,849 € current solution 3,034,608 € proposed solution
Unit cost after 30 years	425.28 €/MWh current solution 375.96 €/MWh proposed solution	373.63 €/MWh 543.84 €/MWh
LCOE	0.81 €/kWh	0.673 €/kWh

The REMOTE demo project should lead in fuel saving of approx. 65000 litres/year versus 65786 l/years in Paradise River, with a LCOE of 0.81 €/kWh versus 0.673 €/kWh (0.991 €/kWh for Ginostra mirror system).

Ambornetti is an off-grid mountain hamlet carrying residential loads. It is characterized by complex and expensive accessibility. The proposed solution includes power generation from PV and local biomass, using an innovative concept of modular gasification. The following figure 66 compares renewable energy production and load:



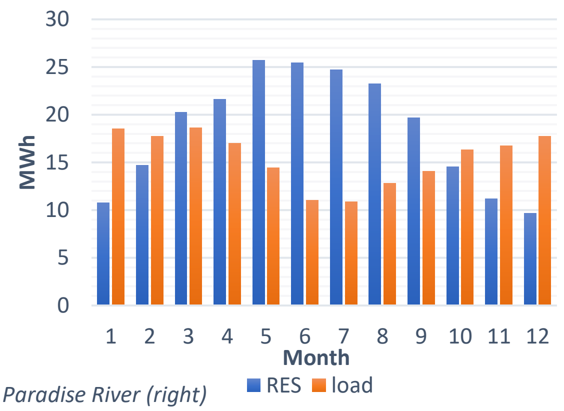


Figure 66 Load and PV production in Ambornetti (left) and Paradise River (right)

In this REMOTE case load profile is more similar to Paradise River one, being quite uniform and slightly higher during winter. Concerning PV production, considerations made for Ginostra are still valid, being the profile responding to solar production on North hemisphere (high during summer, low during winter). The use of biomass source for Ambornetti case allows to add to PV production a constant RES production, leading to less PV area required and thus reducing the maximum gap.

Ambornetti results are available for a P2P system with no battery, the comparison is thus done with Paradise River scenario 2, in tables 15 and 16.

Table 15

	Ambornetti	**Paradise River**
Load covered by RES	91.7%	48.0%
Load covered by fuel cell	8.3%	33%

Load covered by external source	0%	19%

Table 16

	Ambornetti	**Paradise River**
RES to load	64.3%	40.4%
RES to electrolyzer	32.9%	59.3%
RES curtailed	2.8%	0.3%

The combination of biomass and PV allows high load coverage, keeping low curtailment at the same time. In Paradise River the amount of renewables covering the load is lower, but hydrogen utilization is better (+24.7% load covered by FC, +26.4% RES to electrolyser) because of bigger hydrogen tank and more energy gap between September and December.

The following table 17 compare the current and proposed solution for the two case studies.

Table 17

	Ambornetti	**Paradise River**
Current solution	/	150 kW diesel generator
RES	40 kW PV+50 kW biomass	45 kW PV+30 kW wind
P2P	25 kW electrolyzer 50 kW fuel cell	80 kW elecrolyzer 70 kW fuel cell
Storage	30 kWh battery+6 m^3 H2	1400 kWh battery+600 kg H2
NPV after 30 years	1,160,530 € with diesel genset 1,160,839 € proposed solution	2,084,849 € current solution 3,034,608 € proposed solution
Unit cost after 30 years	386.84 €/MWh with diesel genset 354.06 €/MWh proposed solution	373.63 €/MWh 543.84 €/MWh
LCOE	0.42 €/kWh	0.673 €/kWh

The LCOE obtained for Ambornetti is 0.42 €/kWh versus 0.673 €/kWh in Paradise River.

5.4 Conclusions and recommendations

The following table 18 resumes LCOEs found for different combinations of RES configurations and control strategies in Paradise River case study:

Table 18 LCOEs

	Scenario 3 *RES+BATTERY+H2*	Scenario 2 *RES+H2*	Scenario 1 *RES+BATTERY*
PV only	0.991 €/kW	0.799 €/kWh	0.427 €/kWh
Wind only	0.925 €/kWh	0.703 €/kWh	0.374 €/kWh
75% PV/25% wind	0.928 €/kWh	0.792 €/kWh	0.415 €/kWh
50% PV/50% wind	0.956 €/kWh	0.772 €/kWh	0.417 €/kWh
25% PV/75% wind	0.879 €/kWh	0.673 €/kWh	0.391 €/kWh

Table 19, instead, summaries LCOEs found for different alternatives in Colville Lake case study.

Table 19 LCOEs

Current solution *PV+BATTERY*	Proposed solution *PV+BATTERY+H2*	Proposed solution 2 *PV+WIND+BATTERY+H2*
0.414 €/kWh	0.733 €/kWh	0.666 €/kWh

A first consideration is that the use of electrochemical battery is always better than hydrogen tank as storage. In both case studies, in fact, LCOE is the lowest when it is used without hydrogen equipment: for Paradise River it occurs when combined with a mix of PV and wind as RES, while for Colville Lake it settles down 0.414 €/kW when battery is combined with PV.

Another striking aspect concerns the renewable sources: wind energy appears globally better than solar PV: for Paradise River wind-only case (second row in table 18) has always lower LCOE than corresponding PV-only case. Generally, considering latitudes and climate, wind energy turns out to be a better solution for Canada case studies. For both scenarios 3 and 2 configuration with 25% PV 75% wind minimizes LCOE, since a little amount of PV production contributes to levelize the very uneven wind production. An increasing of wind shares in generation mix offers better performances and lower costs, but with some exceptions. Considering the scenario 3, installing 75% of PV and 25% of wind turns better than PV-only and comparable with wind only. For the other scenarios, wind-only is better than RES mix except for 25% PV 75% wind in scenario 2. In scenario 1 wind only minimizes LCOE (lowest value among all alternatives) because when small storage is available (just battery) the higher is the RES production the better are the performances, as explained in Section 2.

For Colville lake the introduction of hydrogen storage reveals to be very cost effective. Adding more RES (wind energy) helps to reduce LCOE till the minimum value of 0.666 €/kWh. An important take-home message from this work is that the quantity of RES is nott as relevant for storage design as the distribution of them.

Hereafter the improvements related to carbon footprint are shown. Specifically, table 20 highlights CO_2 emissions savings for Paradise River when proposed systems are compared to current solution:

Table 20 CO_2 saved for different configurations in Paradise River case study

	Scenario 3 *RES+BATTERY+H2*	Scenario 2 *RES+H2*	Scenario 1 *RES+BATTERY*
PV only	225 t_{CO2}	204 t_{CO2}	204 t_{CO2}
Wind only	233 t_{CO2}	231 t_{CO2}	212 t_{CO2}
75% PV/25% wind	233 t_{CO2}	212 t_{CO2}	218 t_{CO2}
50% PV/50% wind	214 t_{CO2}	220 t_{CO2}	227 t_{CO2}
25% PV/75% wind	233 t_{CO2}	223 t_{CO2}	214 t_{CO2}

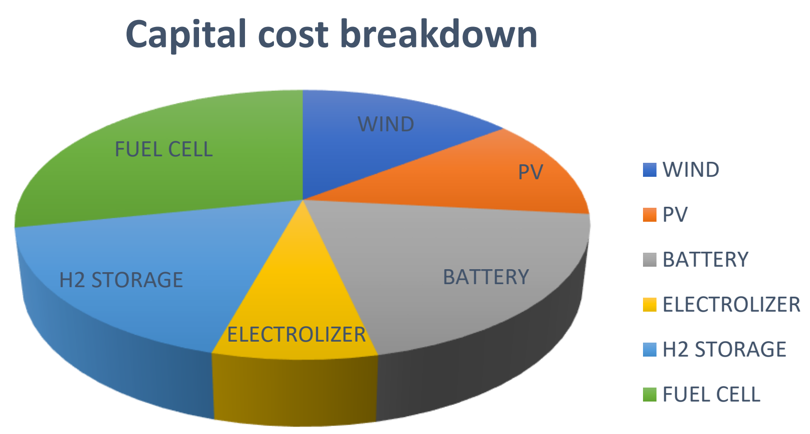
It is worth to note that Scenario 3 column is overall the best, while in table 18 the situation is inverted (highlighted by colour legend), as mentioned in paragraph 4.1. The main result is that the most sustainable H_2 based configuration (calculations made in paragraph 4.2) allows 233 t_{CO2} saved, while configuration minimizing LCOE involves 223 tonnes saved. Table 21 refers instead to Colville Lake case study:

Table 21 CO_2 saved for different configurations in Colville Lake case study

Proposed solution *PV+BATTERY+H2*	Proposed solution 2 *PV+WIND+BATTERY+H2*
69 t_{CO2}	265 t_{CO2}

What comes out is that adding H_2 storage (while keeping the rest of the system unchanged) doesn't affect much the environmental framework (as happened for technical performances, see paragraph 3.6). The introduction of wind turbines, on the contrary, leads to significant amount of CO_2 saved (265 tonnes) because reduces largely external needing.

Despite the environmental benefits, the complete P2P system including hydrogen and battery is definitely not a feasible solution: in the calculation of cash flows capex for hydrogen technologies (fuel cells, electrolysers) are very decisive. By way of example, the following pie chart clarifies the cost breakdown for 50% PV 50% wind strategy 2 scenario in Paradise River.



The hydrogen related sub-systems, that is fuel cell, tank and electrolyser, represent more than 50% of total capex.

Another critical aspect in the calculation of LCOE is diesel price, which turns out to be very low in the Country. Actually, this is a common issue for North America cases which government bodies should regulate through taxation. As seen in the comparison with REMOTE project in paragraph 5.3, higher diesel price would increase opex for diesel generators, as occurs in Europe [31], discouraging their use. Moreover, diesel subsidies for remote communities should be fully accounted for to provide a fair cost comparison of diesel and clean energy and redirected to encourage the development of the latter.

To summarise outlooks for next years (paragraphs 2.17.2 and 3.10), looking at 2025 scenario RES+H_2 option turns out to be better than diesel only option in Paradise River (fig. 67). Scenario 3 is slightly more expensive than diesel only, but not far from it. For Colville lake, in 2025 current scenario and proposed one (comprehensive of H_2 storage) will have approximately the same levelized cost of energy (fig. 68).

The prediction for 2030 sees the complete P2P system (scenario 3) be cheaper even that the LCOE of today's situation in Paradise River. It is the configuration leading to maximum decreasing (-0.575 €/kWh, versus -0.487 €/kWh for scenario 2 and -0.160 €/kWh for scenario 1). Scenario 1, which minimizes LCOE, goes under 0.3 €/kWh threshold and settles down to 0.267 €/kWh. In Colville Lake the proposed system will cost 0.039 €/kWh less than current solution, with LCOE being lower than today's.

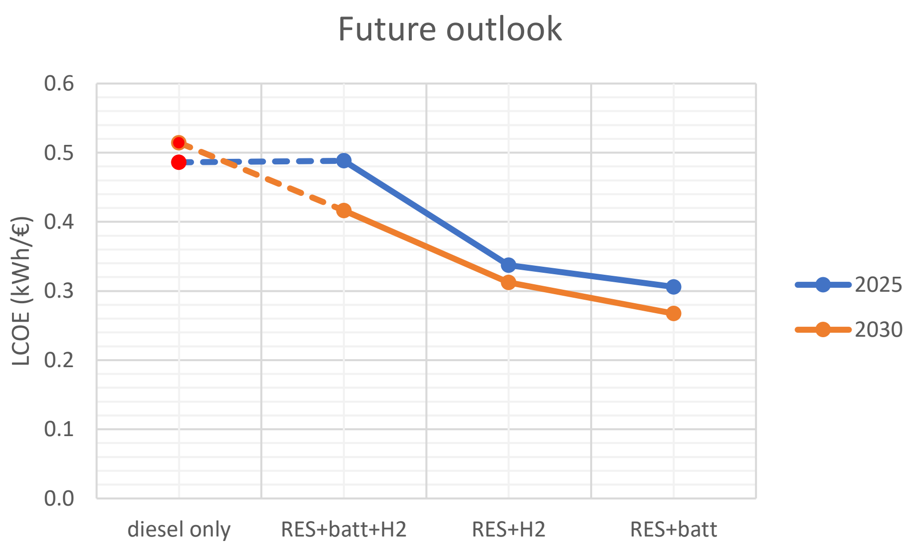


Figure 67 LCOE predictions in Paradise River

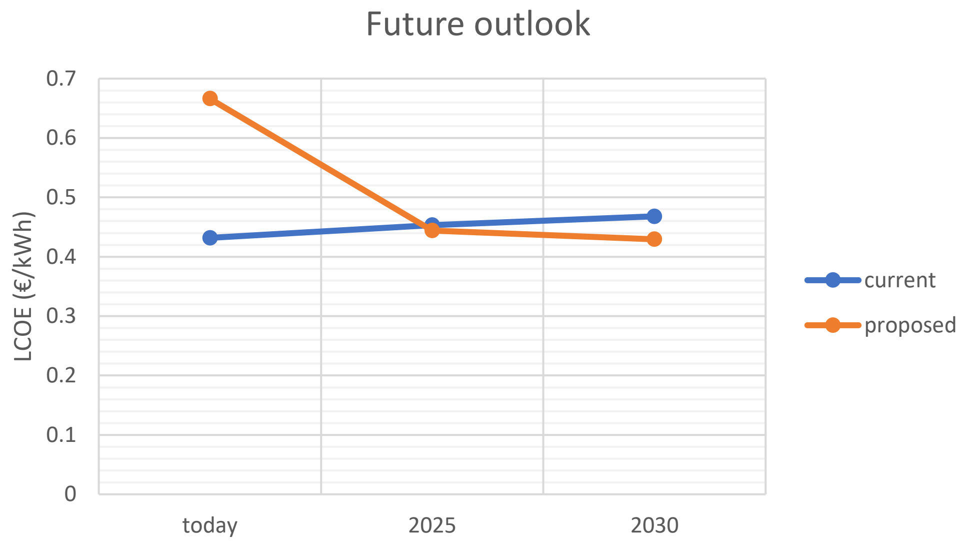


Figure 68 LCOE predictions in Colville Lake

It's significative that most of the conclusions drawn by Khan et al. in the pioneering paper dated 2004 [29] regarding a similar hybrid stand alone system are still valid for this work. Specifically, consideration about the excellent potential of wind resource compared to solar energy, the suitability of wind/diesel/battery systems and the needing of fuel cells cost reduction remain still valid in the present study, even with some quantitative differences (the authors assess that a wind/fuel cell system would be attractive with a fuel cell cost reduction to 15% of its market price). An interesting suggestion pointed out by the authors concerns larger hybrid systems instead of single stand-alone units to bring down the cost of energy. Actually, low demand characterizing some remote communities makes high capital investments not feasible sometimes. An option is to create a local grid whereas more off-grid communities are located quite close geographically, in order to pool electricity demand across more communities. Another chance for communities is to collaborate with private industries to increase the demand. Many communities are located near natural resources, the extraction of whom is energy intensive. This arrangement has worked, for example, for Norman Wells community (NWT) [75].

The use of hydrogen as energy storage is the solution analysed in this work to reduce the reliance on diesel electricity generation in off-grid communities. Of course, other potential solutions exist, both on the supply-side and on demand-side. In the former category fall the use of cleaner electric generators (e.g. fed by natural gas), the installation of renewables sources (biomass reactors, hydro generators, other than PV and wind turbines), the eventual connection to the main grid [76], the design of a proper energy storage. Improvements on demand side involve the increasing of energy efficiency (lighting system, insulation), the installation of smart meters. Because of the variability of electricity demand, in fact, diesel generators are often forced to operate below their nominal capacity, with lower efficiency. With demand response strategy the load can be leveled out throughout the day, incentivizing consumers to alter their consumption patterns.

The current work can be object of further deepening and paves the way to more detailed analyses. The two case studies addressed in this work are intrinsically different. First, two different model have been used to draw the load (Alaska village calculator and Botswana village load profiling). Although they can represent properly the electricity demand of remote communities, an accurate estimation of electricity load is key to design systems without over investing in generation capacity. Upstream from lack of data for remote communities, it is essential that utilities provide historical energy consumptions and load profile data. Also the potential effectiveness of renewable PV source generation has been evaluated differently, but it's based on one hour per day, one day per month data collection. Of course, more refined database means more realistic scenarios. Paradise River case study aims to analyze an innovative system building it from scratch, forecasting load and RES production and studying different alternative systems. The second case study, Colville lake, takes benefit from the PV system already existent, studying what could have changed (on the basis of last year data) if a H_2 storage had been installed together with the battery.

The LCOE tool used to individuate the best solution isn't the only possible decision-making criterion. Other than not considering some aspects, like the environmental and the social ones, it is strongly contingent on assumptions about costs over long periods of time. This is worth especially for diesel generation systems, where recurring costs are predominant. The choice of interest rate impacts strongly LCOE as well. Nevertheless, although other similar studies include a sensitivity analysis on the interest rate, such analysis has been considered not pertinent in case studies addressed here. For instance, in [23] such analysis is led for a case study in Turkey, characterized by unstable economy over last years, while Canada's interest rate has remained constant for several years (average value over last 10 years is just +0.5% than current value [54]). An alternative approach that can be used for decision-making is multi-optimization technique, such as

RPA (Resource Portfolio Analysis). It analyzes different combination of the alternatives of the system, optimizing them meeting system constraints. A widely used software to perform such optimization is HOMER, which allows to evaluate energy alternatives under a variety of assumptions. Several studies for remote communities used this tool. A third possible approach is multi-criteria decision analysis (MCDA), used when multiple criteria conflict among policy alternatives. It involves a variety of criteria that aren't part of typical techno-economic analyses, including qualitative ones (social acceptability, job creation, etc.). A score is then assigned to alternatives basing on relative weighting of criteria, then they are ranked.

Each remote community faces specific challenges, there is no unique solution for them. Each of them has strengths and practical limitations (climate, availability of financing, accessibility, population). The present work assesses that a hydrogen-based storage for a stand-alone system is not commercially feasible at the moment, but could become attractive in 5-10 years, as a result of H_2 technologies price drop. Renewables sources technologies are highly explored, the storage seems to be the key around which their boom revolves. Among the technological alternatives, the ones offering more power and energy capacity are pumped hydro and batteries, other than hydrogen P2P. Hydrogen has low energy density per volume, thus the issue of size could be relevant. Innovative solutions aren't lacking: underground storage, distribution through pipelines are attractive possibilities which have still a great economical barrier. On the other side, P2P suffers from relatively low round trip efficiency. In the process of converting electricity into hydrogen and hydrogen back into electricity, around 60% of the original energy is lost, whereas for a lithium-ion battery the losses of a storage cycle are around 15%. Batteries, however, are unlikely to be used for long-term (because of self-discharge) and large-scale (because a huge number would be needed). Pumped hydro can store electricity for long periods, but cold climate makes difficult its use [77], especially in North Canada. Moreover, remarkable variations are needed. The rise in global spending on research and RD&D on hydrogen technologies over the past few years, combined with the particular moment whereas the shift towards clean and sustainable energy system appears urgent, is more than ever a good sign.

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