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Research Article

HOMER optimization of standalone PV/Wind/Battery powered hydrogen refueling stations located at twenty selected French cities

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Abstract. The current study proposes a model of autonomous Hydrogen Refuelling Stations (HRFS) installed on different sites in twenty French cities powered by renewable clean energy sources. The station is fully powered by photovoltaic (PV) panels, wind turbines with battery storage and involving an electrolyzer and hydrogen tank for producing and storing hydrogen. Using Homer simulation, three scenarios are investigated to propose an optimized model, namely Scenario 1 containing (PV-Wind-Battery) system, Scenario 2 with (Wind-Battery) technologies and Scenario 3 with (PV-Battery) components. The otimization process executed demonstrates very competitive levelized cost of energy (LCOE) and levelized cost of hydrogen (LCOH) especially for the third scenario solely based on PV power with LCOE in range $0.354-0.435/kWh and a LCOH varying within $13.5-16.5/kg, for all 20 cities. An average net present cost (NPC) value of $ 1,561,429 and $ 2,522,727 are predicted for the first and second architectures while least net present cost of $1,038,117 is estimated for the third combination solely based on solar power according to all sites considered. For instance, minimum values are obtained for Marseille city with LCOE=$ 0.354/kWh and a LCOH=$ 13.5 /kg in conformity with the minimum obtained value of NPC value of $886,464 with respect to the winner third scenario. In addition, more costly hydrogen production is expected for Grenoble city especially for scenario 1 and 2 where wind turbine technology is introduced. On another hand, thorough analysis of PV/wind hydrogen techno-economic operation is provided including improvements recommendations, scenarios comparison and environmental impact discussion.

Keywords: Hydrogen refuelling station, Renewable resources, techno-economic analysis, HOMER software, Levelized cost of hydrogen

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1. Introduction

The global energy demand especially in the European union countries keeps growing each year with its various form such as heat and electricity while remaining an indispensable requirement of the modern life worldwide. This electricity consumed in the daily lives is derived from various electrical appliances and is not only used in urban or industrial areas but also in rural areas consuming lot of energy (Gebre and Gebremedhin 2019, Oladeji *et al.* 2021, Samy *et al.* 2022). Though, much of today's energy is obtained by consuming large amounts of oil and coal and emitting carbon dioxide, which causes global warming (Ariae *et al.* 2019, Gil and Bernardo, 2020). Such energy usage cannot be said to be "sustainable" in terms of the finite nature of resources that will eventually run out causing further environmental problems. This concern pushed the whole international community to accept new energy use in order to reconsider the way of conventional energy society and to solve various problems especially climate change which is an urgent issue in the whole world (Chau and Le 2022, Nono Seutche *et al.* 2021, Sims 2004, Owusu and Asumadu-Sarkodie 2016). Among the promising solutions to climate change is the production of green hydrogen that can be fully induced from renewable energy resources enabling to power water electrolysis (Lahlou *et al.* 2023, Dincer 2002; Abad and Dodds 2020, Dutta 2014). Nevertheless, until 2020, 99% of hydrogen production is still a hydrogen derived from fuel sources emitting carbon dioxide. which is not considered as green hydrogen. Contrarily, the green H_2 which is produced by steam reforming of natural gas represent 95% of the market but this hydrogen type has significantly high carbon dioxide emissions. On the contrary, green hydrogen, that is derived from water electrolysis process and by emission-free sources, only represents less than 0.1% of total hydrogen production. However, thanks to wind and solar resource wealth and government strategies, many countries can be turned into major suppliers of H_2 renewables-based in the coming years by quickening the building out of their local renewable capacities. In fact, the US Department of Energy (DOE) is estimating that the cost of hydrogen production will probably diminish from $6/kg in 2015 to as low as $2/kg by 2025 (Miller *et al.* 2020). Nonetheless, one of the major factors behind the low usage of green H_2 produced by electrolysis of water is the high cost of its production compared to classic sources of energy like the gasoline or coal. Despite its current higher cost, the low emission of green hydrogen motivates countries to adopt electrolysis of water using renewable sources to produce the green H_2 to reach the net-zero world goal. In this context, France was among the first countries to identify the full potential

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of hydrogen, in particular its ability to reduce emissions of greenhouse gases while being competitive (Le Duigou *et al.*, 2013). Starting from 2018, France has chosen to support the sector and has devoted resources to it as part of the investment for the future French program. The challenge is ecological, technological, and economic. In fact, the idea is to create and structure a cutting-edge industrial ecosystem that is internationally competitive. Besides, the government tends to massively accelerate these investments by committing 7 billion euros by 2030, of which 2 billion euros from the recovery plan between 2021 and 2022. The French objective is thereafter to combine the technological development and ecological transition. These 7 billion euros will be invested according to three priorities, decarbonization of industry to contribute to achieving the carbon neutrality in 2050, the development of mobility heavy hydrogen fuels as well as the support of research excellence and the development of training offers. Consequently, the challenge of this strategy is expected to promote rapid scaling up industry to enable a significant reduction in the cost of production.

Among the few studies dealing with HRFS for the French case, Kim *et al.* (2021) considered the French capital Paris as a case study to investigate the feasibility of hydrogen stations using optimal deployment methods to predict the Pareto optimal solutions that can be selected by policy makers based on their preferences. The authors claimed that the proposed methodology allows to determine the optimized positions of one or two additional stations from a short-term perspective. Besides, the suggested procedures may provide a weighted sum optimal solution, that can lessen the total distance between customers and their assigned stations while extending the distance between the hydrogen stations. In addition, Tlili *et al.* (2020) compared five hydrogen pathways starting from the production step up to the refuelling station and facing the options of pipeline and truck according to the French case. Three demand scenarios are studied, ranging from 1% until 15% of market penetration. The outcomes of their studies show that economies of scale that may be driven by higher market penetration rates can drastically reduce the hydrogen cost.

On another hand, one of the most liquid fossil fuels consuming sectors in the world and specifically in France (Fig. 1(a)) is the road transportation which promotes the use of renewable energy instead of conventional power generation methods (Gardner 2009, Sharma and Ghoshal 2015). In fact, green hydrogen produced with renewable energies is expected to expand in the future as a fuel for vehicles instead of gasoline, steelmaking, and power generation application (Guilbert and Vitale 2021). In this vein, a hydrogen car is a vehicle that runs with hydrogen instead of gasoline. Above all, it generally refers to a vehicle equipped with a hydrogen engine (hydrogen fuel engine) that burns hydrogen by improving the conventional internal combustion engine such as diesel engine. On the other hand, there are also automobiles that run by using a fuel cell that generates electricity through a chemical reaction between hydrogen and oxygen to turn a motor. This is a type of vehicle called a fuel cell vehicle (FCV) which generates electricity to power a motor and are becoming more and more popular (Momirlan and Veziroglu, 2005). Because it uses hydrogen for power supply, it is also called a "hydrogen car". Currently, in the case of fuel cell vehicles, the hydrogen, which is the used fuel, is basically replenished at dedicated stations such as hydrogen stations (Eberle *et al.* 2012). Compared to petrol cars, one of the great benefits of using the hydrogen-powered vehicles is the fact that they only emit steam (water) during operation. They emit neither carbon dioxide nor exhaust gases containing other constituents. Nitrogen oxides are produced during combustion, but this is also less than in gasoline engine. However, hydrogen-powered vehicles also pose challenges (Kyjovský *et al.* 2023). According to the users' point of view, there are not enough hydrogen stations that can supply hydrogen. Nevertheless, in the long term, it is expected that "zero carbon dioxide" hydrogen stations, which electrolyze water with renewable energy, will become widespread (Genovese and Fragiacomo, 2022). From this perspective, France announced an inauguration of the first "green" on-site hydrogen refuelling station in 2017 installed in the French city of Sarreguemines to experience the use of hydrogen to fuel cell vehicles. This first HRFS fully powered with renewable energies inspired the current study to discuss the technical and economic feasibility of using hybrid clean technologies to produce green hydrogen in different French cities. In fact, multiple countries are encouraging the installation of HRFS totally powered with renewable technologies such as photovoltaic and wind turbines. In this line, for a hydrogen station, the method of supplying hydrogen to the station is important. Two main ways exist to do this: the "on-site type" that produces hydrogen from liquefied petroleum gas (LP gas) at the site of the hydrogen station (Romagnuolo 2023), and the "off-site" station that transports compressed hydrogen and liquid hydrogen produced outside, such as refineries and chemical plants, to the station (Tang *et al.* 2022, Pan *et al.* 2016). Among the studies dealing with off-site HRFS, one can cite the work of Gökçek and Kale (2018a) who designed and optimized a hydrogen refuelling station by testing two hybrid systems containing multiple components, namely the wind turbines, electrolyser, and battery storage. The LCOH of the refuelling station installed in a Turkish site of Izmir-Cesme is determined to be within the range of $7.526 -7.866/kg for different combinations of wind/Electrolyser/battery technologies. Likewise, Ayodele *et al.* (2021) carried out a technical and financial study of hydrogen refueling station based on wind power for different cities in South Africa. The city stations are modelled to daily feed 25 hydrogen-powered cars every day having a capacity of 5 kg each. The cost of hydrogen is predicted to range between $ 6.34 /kg to $ 8.97 /kg and seems to be further competitive especially for coastal cities of South Africa. In addition, the authors found that the proposed model can annually mitigate the carbon oxide and carbon dioxide by respectively 0.133 tons and 73.95 tons. In addition, the integration of an electric vehicle or hydrogen vehicles into a zero-energy building using suitable control strategies is explored by Cao (2016). The author claimed that a combination of a square meter area of 195.8, 160.2, and 142.4 of a photovoltaic panel or a rated wind turbine power of 16, 12, and 12 kW can meet the annual net-zero energy-emission balance for the building according to the hydrogen vehicle, the electric vehicle, and no vehicle, respectively. He also suggested that the zero-energy system can be obtained using the excess renewable energy hot water recharging strategy or also by lessening the condition to discharge the vehicle storages relative to domestic usages. Lee *et al.* (2018) proposed a model of a hydrogen refuelling station involving a PEM electrolyzer and studied its financial profitability. The authors economic assessment is performed via the cash flow diagram, the net present value (NPV) and discounted payback period. It is found that including high pressure proton exchange membrane water electrolysis is observed to blead to better profitable system in terms of NPV cost and short discounted payback periods.

On another hand, the financial cost of hydrogen stations remains one of the main concerns when establishing a hydrogen refuelling station totally powered by renewable technologies.

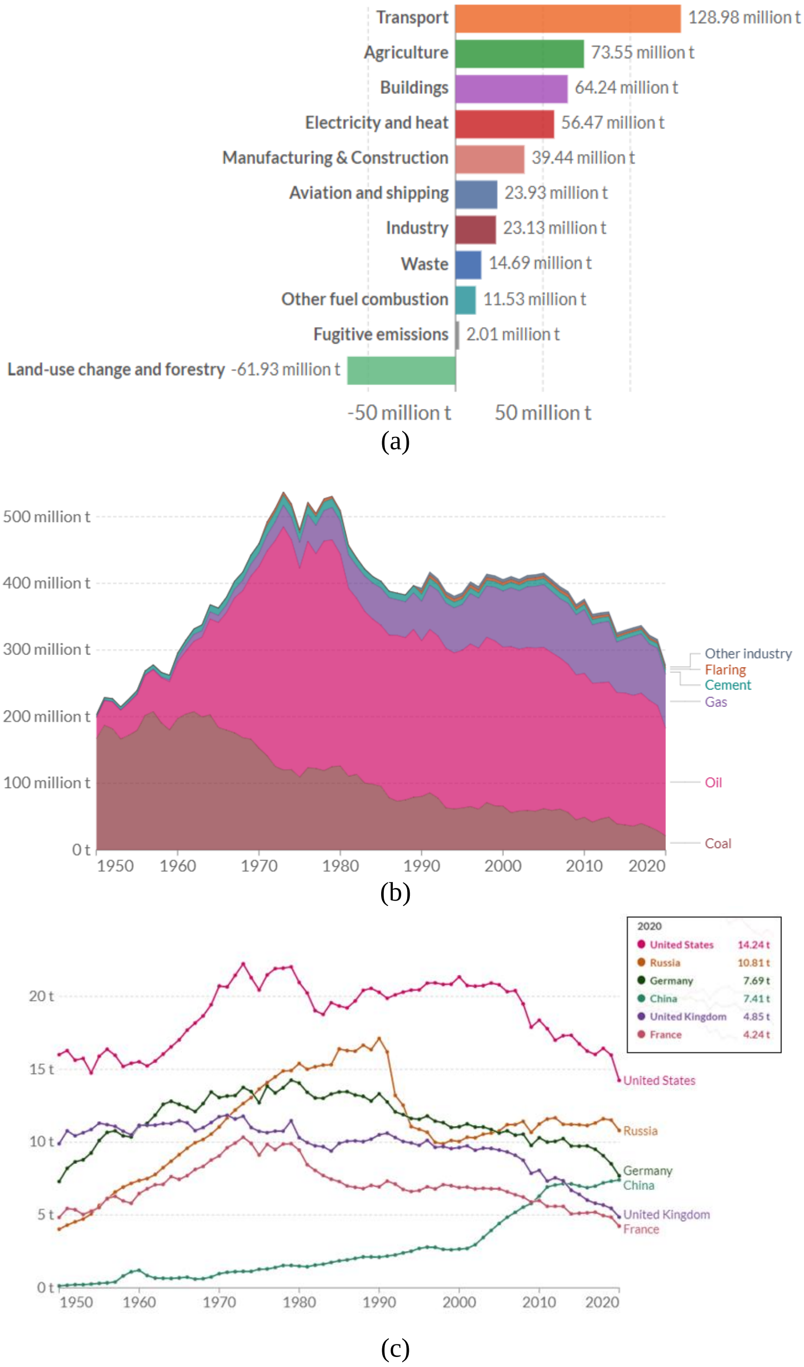


Fig. 1 (a) Annual (CO_2) emissions evaluated in tons per year that are derived from different fuel types in France. (b) Greenhouse emissions amount share by sector in France since 1990 (c) comparison of the CO_2 amount measured in tons/capita resulting from fossil fuels and industry with respect to the top five most emitter countries (data from 1950-2020).

This cost depends on the renewable equipment, the production techniques, as well the costs added due to storage, compression, and distribution of hydrogen. Furthermore, achieving a stable power generation in the HRFS regardless of day and night and seasons is one of the main goals of using a hybrid system involving multiple power generation resources, namely the wind and solar radiation in the station. Since wind power can be generated on bad weather and solar power can be generated on weak winds, a stable power supply is possible. In this context, Perna *et al.* (2022) discussed the technical and financial feasibility of an on-site HRFS producing hydrogen from various production technologies and sources such as the Ammonia, biogas, and water electrolysis. The author performed the analysis using HOMER software for technical sizing and economic optimization to adopt the best configuration for HRFS. They reported the lowest LCOH for Ammonia based scenario where a varying in the range of EUR 6.28 /kg ($6.28 /kg) to 6.89 EUR/kg ($6.89/kg) are obtained. Siyal *et al.* (2015) also carried out a numeric techno-economic study using HOMER software of a HRFS fully fed by wind energy to daily refuel 200 vehicles in three different Swedish sites. Comparison of both models V82 and V112 wind turbines is performed in terms of hydrogen production costs and energy outputs to get the optimized system corresponding to each site. Minutillo *et al.* (2021b) performed a technical and financial study of a HRFS based on Ammonia-to hydrogen production for different design concepts. The economic assessment is carried out in terms of the levelized costs of electricity (LCOE) and hydrogen (LCOH), the internal rate of return, the profitability index, and the discount and payback period. The values corresponding to LCOE is obtained to be in the range EUR 0.447/kWh ($ 0.447/kWh) to EUR 0.242/kWh ($ 0.242/kWh), while the LCOH is varying between EUR 6/kWh ($6/kWh) and EUR 10/kWh ($10/kWh) for the different financial scenarios and scenarios proposed. Viktorsson *et al.* (2017) estimated the LCOH for a HRFS installed in the Belgium Halle city. The study reveals that the levelized cost of hydrogen can be minimized within twenty years until the value EUR 10.3/kg ($ 10.3/kg) in case the LCOE reaches EUR 0.04/kWh ($ 0.04/kWh) and further operating hours are applied. In addition, a value of EUR 6.8/kg ($ 6.8/kg) can be obtained if the initial capital cost of project can be also lowered by 80%.

According to the data based on the work of Ritchie *et al.* (2020), displayed in Fig. 1 (a), the transport sector in France is the first responsible for the global CO_2 emission compared to other sectors like agriculture, building or industry. This boosts the country to search for alternative non-pollutant source of energy and where the hydrogen remains one the most leading source especially in the transport sector. On another hand, the reliance of the French country energy system on hydrocarbon resources basically on oil, gas and coal has partly contributed to the country being within the 20 top largest ranked countries that are responsible for the global CO_2 emission with 4.24 t/capita in 2020 (Fig. 1 (c)). With such data, France was one of most world's emitter in 2020 compared to the five classical five first ranked countries which produce the most amount of carbon dioxide (CO_2), namely the United States, China, Russia, Germany and the United Kingdom (Fig.1. c).

On the other hand, multiple studies are found in literature proposing models of hybrid systems incorporating renewable technologies containing the hydrogen power for residentials communities or industrial areas worldwide (El Hassani *et al.* 2023, Navas *et al.* 2022, Liu et 2021, Oueslati 2021, Eteiba *et al.* 2018, Tazay *et al.* 2020, Mokhtara *et al.* 2021, Samy *et al.* 2020, El-Emam *et al.* 2022, Wu and Skye 2021, Duman and Güler 2018, Rezk *et al.* 2020) as well as in France (Panayiotou *et al.* 2012, Islam 2018, Mohammed *et al.* 2019, Herez *et al.* 2021). Nevertheless, to the best knowledge of authors, studies dealing with hydrogen refuelling station using renewable energies in France is still scarce in literature despite the first refuelling station is already operating in the town of Sarreguemines in the East of France and serving a small fleet vehicle of model Kangoo ZE-H2 that is equipped with fuel cell range-extenders. So far, the whole transport sector cannot be really and totally considered as "friendly to environment". The majority of existing HRFS in France are still off-site stations where the hydrogen is derived from non-renewable techniques and transported to the station to supply the vehicles with the compressed hydrogen. From this point of view, the current study discusses the feasibility of using renewable energies to enable production of hydrogen and power fuel cell electric vehicles which represents an exciting opportunity to expand the use of green hydrogen in clean transport. In addition, on-site refuelling station will eliminate the cost and reduce risk of hydrogen transportation which are common drawbacks in the off-site hydrogen stations compared to on-site ones.

2. Worldwide HRFS and French context

According to annual data published by the specialized site of TÜV SÜD (2022), a total number of 685 HRFS are operating worldwide with new 252 planned refuelling stations spread in 33 different countries. For instance, an encouraging number of 142 hydrogen refueling stations went into operation worldwide all over the world in 2021 only (TÜV SÜD 2022). In the old continent Europe, Germany recorded the strongest growth with 101 stations out of 228 existing in Europe. Boosted by the need to diversify its sources of energy, Asia is now leading the migration to hydrogen energy use in HRFS with 363 stations established at different countries and sites. With 195 station installations, it is well ahead of those in Japan, followed by China and South Korea with 105 and 95 HRFS, respectively.

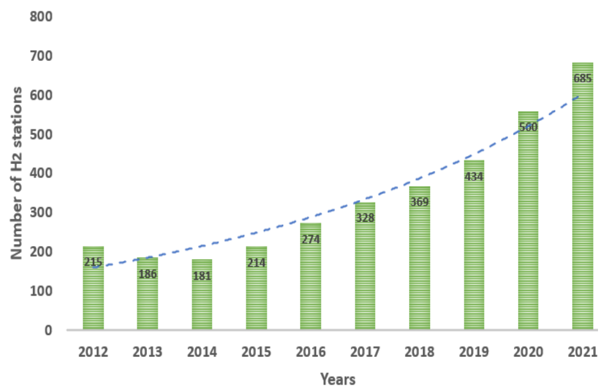


Fig. 2. Worldwide evolution of HRFS number since 2012 (TÜV SÜD, 2022).

Overall, about twenty countries in the world have a hydrogen strategy committing more than 37 billion dollars investment in hydrogen energy. While the vast majority of investments finance the production of renewable hydrogen, the national strategies of different countries reveal differentiated approaches (France-hydrogene 2022). Meanwhile, driven by the objective of a reindustrialization guaranteeing its technological and energy sovereignty, France is investing in the construction of a complete and integrated ecosystem, from production to uses, including the manufacture of equipment. The resulting energy needs to not exclude the use of imports of renewable hydrogen. Therefore, this study is intended to provide valuable data information for the technical and financial assessment of possible future emerging HRFS based only on renewable resources to diverse the fuel energy and transport techniques that can suit local French environment within the European Union.

Until 2022, France counts 40 operating hydrogen refuelling stations illustrated in Fig. 3. Moreover, concrete refuelling station plans are already in place for 82 additional HRFS that are whether under construction, or also planned which leads to a total of 122 HRFS expected to be totally operating within few years. Besides, the French government is planning to diversify the filling transport category, for instance 2 HRFS are already established for boats powered by hydrogen in La Rochelle and Nantes coastal cities.

Today, considering the amount of the 900,000 tons of hydrogen produced and consumed each year in France, more than 95% comes from fossil fuels and in particular from natural gas by steam reforming. Industrial solutions are therefore widely proven; yet they are sources of CO_2 and greenhouse emissions.

However, despite the French government encouragement, the use of decarbonized hydrogen especially in industry is still insufficient with only 5 % (45,000 tons) of the overall industrial production market using the green hydrogen and 95% of the hydrogen production is still using carbon emitting techniques in 2022. In fact, the hydrogen is then said to be "carbon-free" or decarbonized because neither its production nor its use emits CO_2. Hence, given its low CO_2-emitting electricity mix, France has assets for producing decarbonized hydrogen that can be produced by electrolysis of water, using renewable energies. The use of this decarbonized hydrogen will thus reduce CO_2 emissions into the atmosphere. This will also contribute to achieving the objective that was set as part of the national low-carbon French strategy for industry: 53 million tons emitted per year in 2030 compared to 80 million tons emitted per year today.

In 2018, France adopted a hydrogen deployment plan for the energy transition led by the Ministry for Ecological and Solidarity Transition (Ministry Report 2018). The action plan is based on three axes: the production of hydrogen by electrolysis for industry, the promotion of clean transport sector in complementarity with the battery sector, and hydrogen as an element for stabilizing energy networks. Meanwhile, among this strategy, a general decree on hydrogen stations was introduced by the government. The decree targets the stations, that are open or not to the public, which produce more than 2 kg of hydrogen per day and where the hydrogen is transferred to the vehicle tanks. The text sets the rules relating to the compliance of hydrogen stations, the operation of facilities, safety, and the management of water, waste, and noise (Décret n° 2018-900, 2018). Accordingly, in 2022, the results of the French strategy in decarbonizing the transport sector using hydrogen as a fuel is described by 400 Light vehicles, 31 buses in service, 175 bicycles, 280 forklifts, and 2 boats. The government is expecting to rise these numbers by 2030 up to 300,000 Light vehicles, 5000 heavy vehicles, 1000 boats, 250 trains with deployment of new 1000 H_2 charging stations.

3. Methodology

3.1 Site locations with corresponding solar and wind potentials

In the current study, 20 French cities are selected according to the sites where most of the off-site hydrogen stations that are operating are established to analyze the viability of the deployment of on-site hydrogen stations fully powered by renewable energies. Similar load profiles are considered for all twenty cities. In fact, all cities are characterized by high vehicle traffic throughout the year and possess big car numbers which present valuable research areas for future hydrogen filling stations. In Fig. 3 are illustrated the geographic positions of the twenty HRFS under consideration located in different French cities.

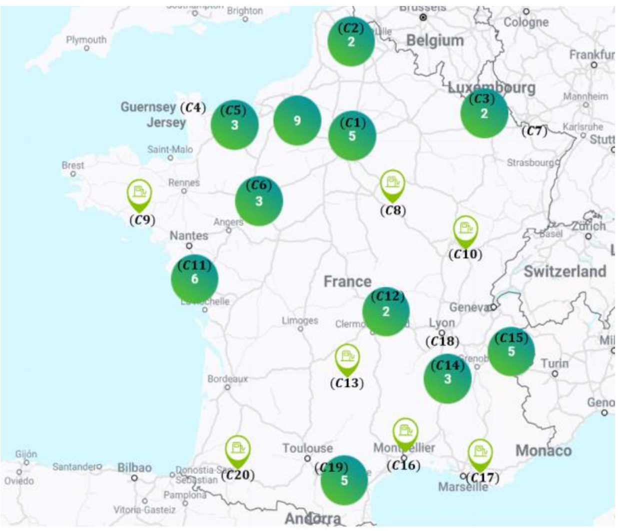


Fig. 3. Locations of the 40 operating hydrogen refuelling stations in France with relative number in each city and positions of the twenty investigated sites in the current study (C1-C20) (data explored from *France-hydrogene* 2022)

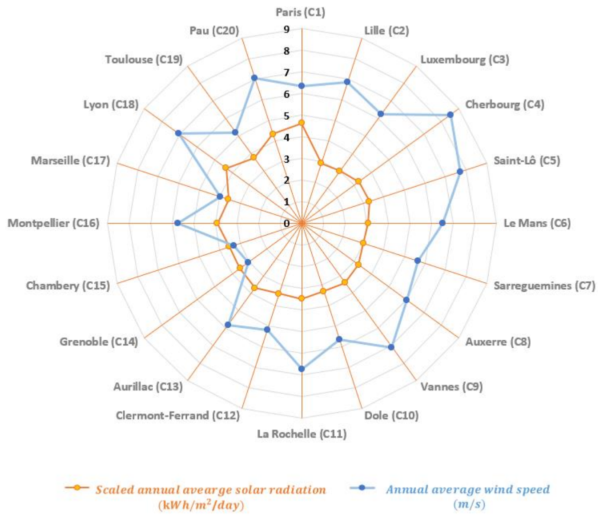
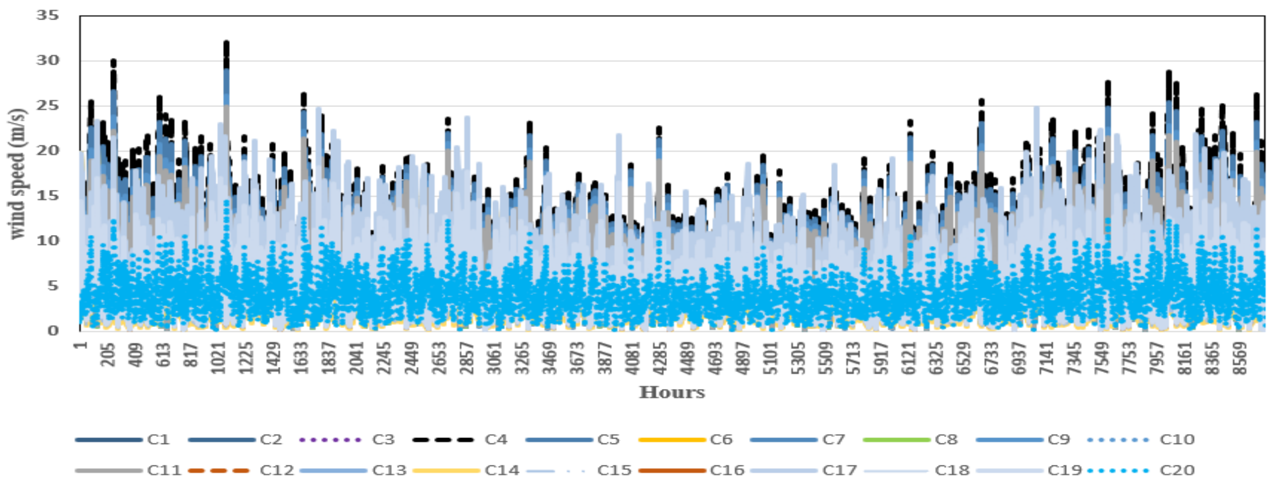


Fig. 4. Radar chart of annual average solar radiation and average wind speed in the twenty selected French sites

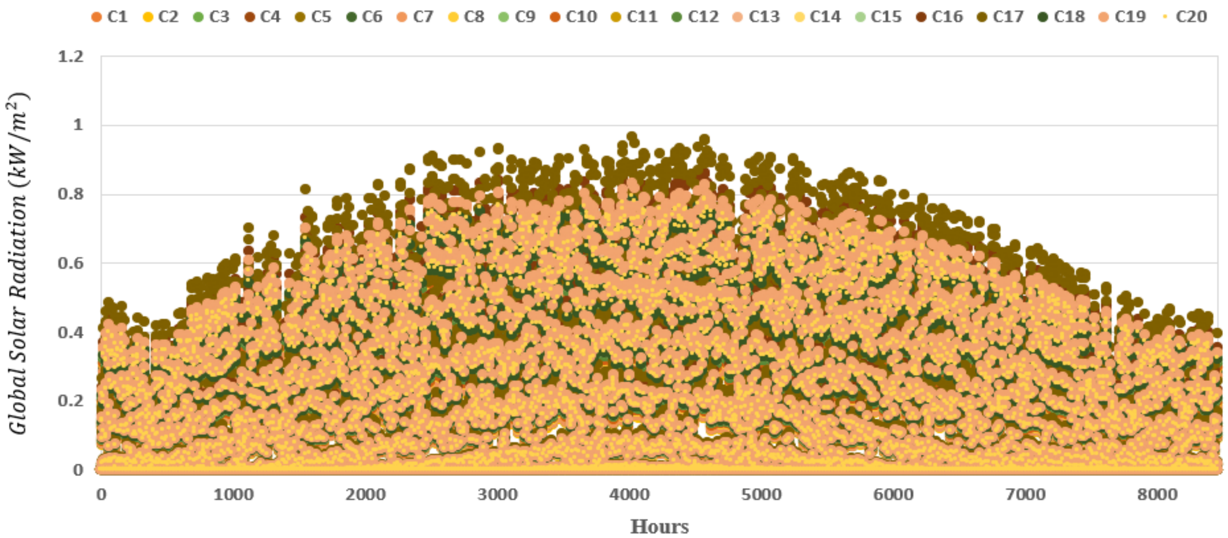
On another hand, the meteorological data obtained from database published by the National Aeronautics and Space Administration (NASA) (HOMER, 2022) and the National Renewable Energy Laboratory are utilized as input data to simulate the hybrid hydrogen refuelling stations in the various sites. Considering the wind potential of the geographic sites considered, the hourly wind speed during the year and annual average wind speed predicted are summarized in Fig. 4 and Fig. 5(a). As can be seen, highest wind power is obtained in the winter months between November and February in all cities and which lessens in spring and summer. More significant average wind speed is reported in Cherbourg (C4), Saint-Lô (C5), and Vannes (C9) with values ranging between 7.1 and 8.51 m/s while the annual average wind speed for the twenty cities is 5.991 m/s. On another hand, conversely to the wind power, the global solar radiation illustrated in sub-Fig. 5(b) demonstrates that summer months are manifested by more pronounced solar power that especially strengths in July-August with a scaled annual average solar energy yield of 3.535 kWh/m^2/day according to all cities. It is also observed that cities of Paris (C1), Marseille (C17) and Lyon (C18) are the sunniest French cities relatively to the other ones with a daily annual solar yield that exceeds the 4.3 kWh/m^2/day. It is also worth mentioning that when optimizing the PV model, the corresponding optimal tilt angle of orientation for the PV panel is taken to be 35° from the horizontal axis for all sites which is the inclination adopted on most PV array installations in France. This fixed optimal angle allows better solar energy yield and hence better hydrogen and energy production in the predicted refuelling stations across the twenty sites.

3.2 HRFS components

To generate the power needed to supply the clean hydrogen, the HRFS model involves various renewable components, namely PV panels, Enercon 53 model wind turbines, PEM electrolyzer, hydrogen compressor, hydrogen tank, converters,



(a)



(b)

Fig. 5. Hourly (a) wind speed and (b) global solar radiations during the year for the twenty regions under consideration.

battery storage system and a dispenser. The schematic model adopted of the refuelling station is illustrated in Fig. 6 (a). In addition, to establish an optimized system technically and financially for the various geographic sites, three scenarios have been adopted, namely Scenario 1 (PV-Wind-Battery) system, Scenario 2 (Wind-Battery) and Scenario 3 (PV-Battery) as schematized on Fig 6 (b).

3.3 Hydrogen load

In Fig. 7 we plot the daily hydrogen load profile implemented in the HOMER software. In the current study, we adopted 25 vehicles of the Japanese model car named Toyota Mirai. This car model has an average hydrogen tank of 5 kg meaning 125 kg/day of hydrogen load demand for the 25 cars considered. The fuelling process of the Mirai car takes only about three minutes and can achieve a 500 km by consuming 0.76 kg of hydrogen per km with zero carbon dioxide emission which makes it an excellent economic choice and a very friendly car to environment. As seen in Fig. 7, the peak hours of hydrogen quantity needs are observed between 12h and 14h, while it lessens starting from 7 pm until 6 am with only a 2 kg/h of hydrogen consumption. Furthermore, a daily scaled annual average electrical load of 443.05 (kWh/day) with a maximum peak power of 32.12 kW derived from the renewable equipment is supplied to HRFS components to produce the needed hydrogen.

3.4 Wind turbine model

In the case of the wind turbine model (here Enercon E-53 (800 kW)), the HOMER software computes the wind speed at the turbine hub height taking into account the wind shear. The power curve of the wind turbine with the corresponding power coefficient (Cp) profile are illustrated in Fig. 8. Moreover, characteristics details are also provided in Table 1. When modelling the wind turbine in HOMER, a logarithm profile is implemented supposing that the wind speed is proportional to the logarithm of the height above ground. An equation describing the power law profile which is the wind speed ratio at the hub height v_{hub} (m/s) to the wind speed at anemometer height v_{anem} (m/s) is evaluated as follows:

$$\frac{v_{wind}}{v_{anem}} = \left(\frac{z_{hub}}{z_{anem}}\right)^{\alpha} \tag{1}$$

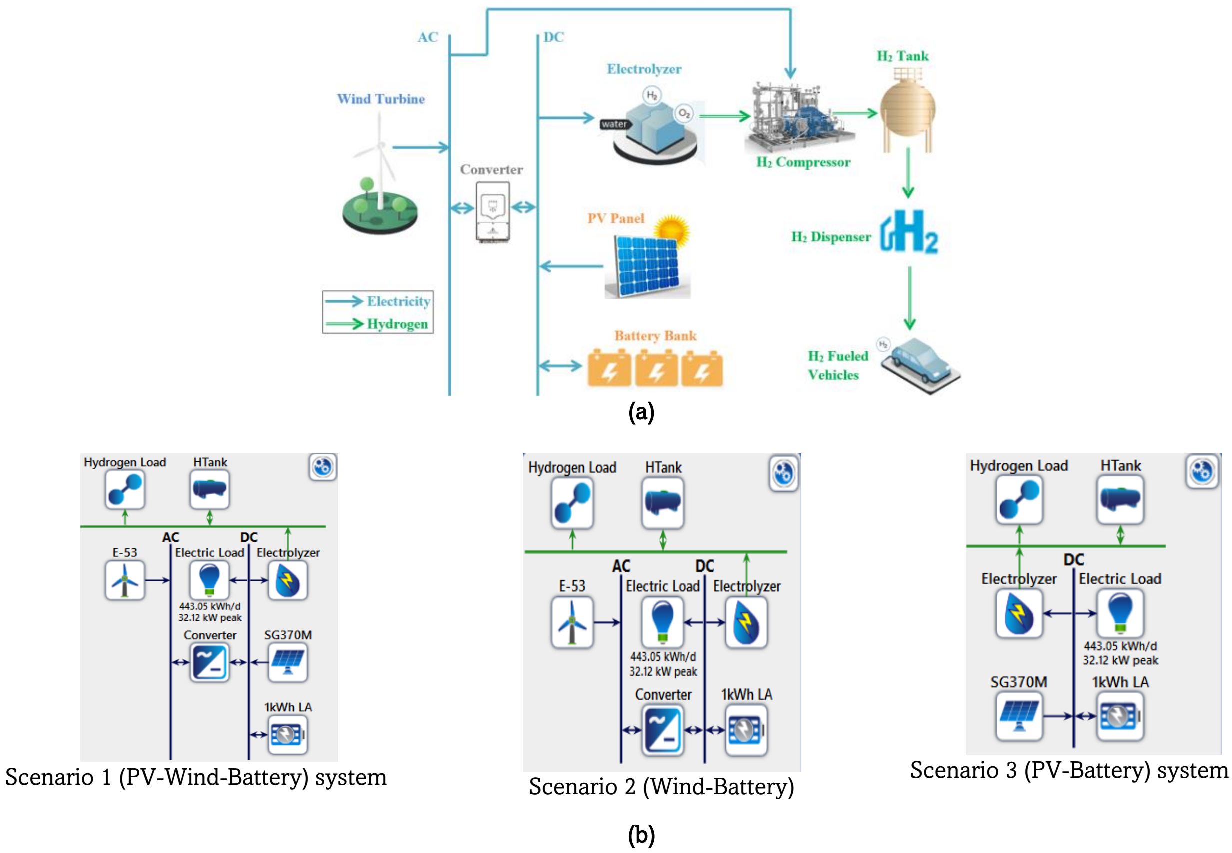


Fig. 6. (a) HOMER model describing the components of the hydrogen refuelling station with (b) corresponding three scenarios adopted in the simulations.

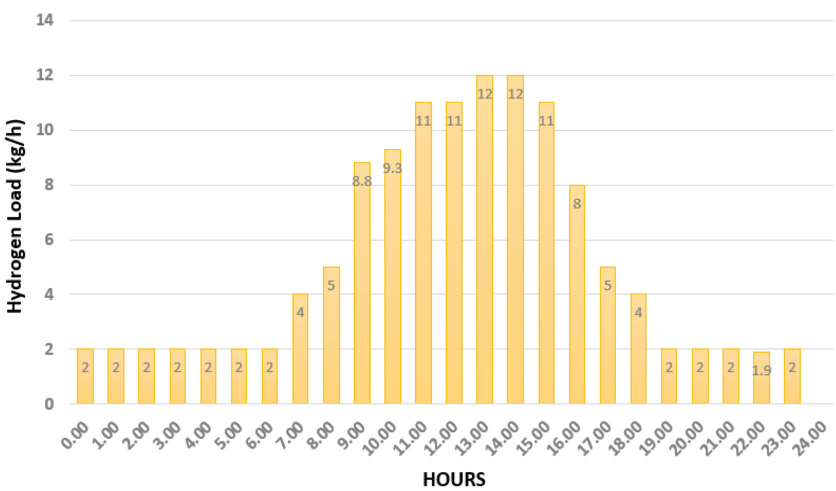


Fig. 7. Hourly H_2 load profile of typical refuelling day in the HRFS.

Where z_{hub} andz_{anem} and α are the hub height of the wind turbine, the anemometer height and the power law exponent, respectively.

Finally, HOMER predicts the wind turbine output (P_{wind}) by forcing a correction factor to compute the actual air density using the following equation:

$$P_{wind} = (\rho/\rho_0)P_{wind,STP} \tag{2}$$

Here, ρ denotes the air density (kg/m^3), and ρ_0 and $P_{wind,STP}$ (kW) are the air density and power output under standard conditions, respectively.

3.5 PEM electrolyzer

In the current study, a proton exchange polymer membrane electrolyzer (PEM) is implemented in all computations. It is important to mention that the choice of utilizing the PEM

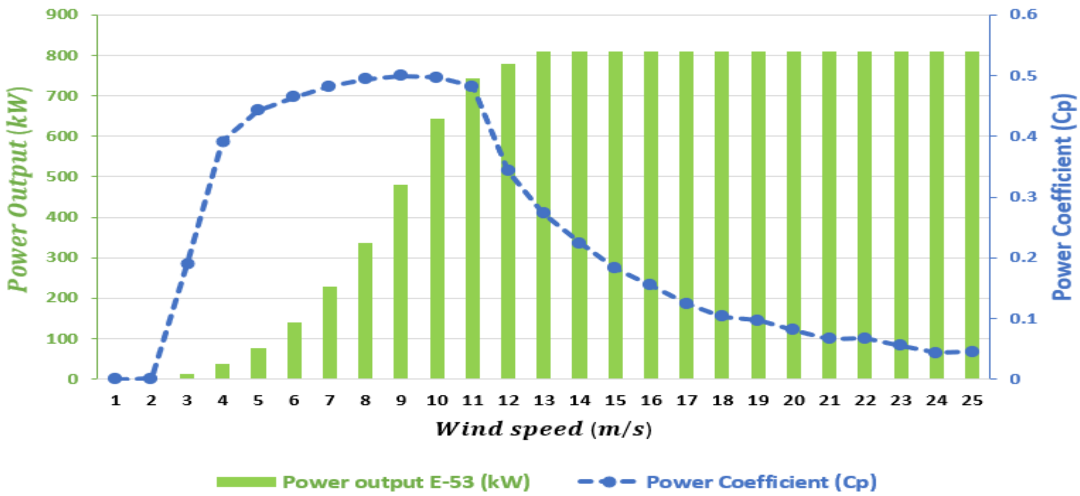


Fig. 8. Plot of the Power Coefficient (Cp) (blue dashed line) and electric Power output in kW (green bars) with respect to the wind speed (m/s) for the considered Enercon E-53 (800 kW) wind turbine

electrolyzer is given by the fact that this type is very promising in producing hydrogen: it is compact, electrically efficient and allows a finer electrolyte than alkaline electrolysis. Furthermore, PEM electrolyzer produces very pure hydrogen (little or no pollution by the electrolyte) and requires very little maintenance and can be powered by electricity from renewable sources. In terms of financial point of view, PEM electrolyzer can operate at much higher densities and capable of reaching values greater than 2A/cm², which reduces operational costs and, potentially, the overall cost of electrolysis. The principle of PEM electrolysis differs from that of alkaline electrolysis in that the electrolyte is a solid electrolyte, composed of a conductive membrane of protons; the electrodes are deposited on either side of this polymer material.

The reaction at the anode also called "Oxygen Evolution Reaction" (OER) is given by:

$$H_2O\ (l)\ \rightarrow\ ½\,O_2(g) + 2H^+(aq)\ +\ 2e^- \quad (3)$$

Then, the H⁺ protons migrate towards the cathode through the membrane under the effect of the electric field and the concentration gradient in which they are reduced to molecular hydrogen manifested by the cathode reaction. The equation is known by the Hydrogen Evolution Reaction (HER) expressed as following:

$$2\,H^+(aq)\ +\ 2e^-\rightarrow H_2(g) \quad (4)$$

In the current study, the efficiency electrolyzer is held at a percentage 85% of higher heating value (HHV).

3.6 Compressor and Hydrogen storage tank

In practice, both liquid hydrogen and high-pressure hydrogen can fill fuel cell vehicles with hydrogen. As the hydrogen station is a dispenser equipped with a nozzle for supplying hydrogen to vehicles similarly to classical gas station, a hydrogen tank is needed to store hydrogen at pressure between 350 or 700 bars. In fact, as a PEM electrolyzer is used with an output pressure of nearly 14 bar, a compressor, simulated by a corresponding primary electric load, is then compulsory to raise hydrogen to an appropriate pressure from 14 to 700 bar and supply the fuel cell electric vehicle at minimum pressure of 300 bars. The rated power needed to compress the hydrogen is expressed in the HOMER model by means of the following equation:

$$P_{comp} = C_{p,H_2}\frac{T_1}{\eta_c}\left[\left(\frac{p_2}{p_1}\right)^{\frac{r-1}{r}} - 1\right]m_c \quad (5)$$

In this equation, the parameters C_{p,H_2}, T_1 , η_c , r and m_c denote respectively the specific heat of hydrogen at constant pressure (14.304 kJ/kg K), the inlet gas temperature of hydrogen compressor (293 K), the compressor efficiency, r is the isentropic exponent of hydrogen taken to be 1.4 and the gas flow rate (kg/s). Moreover,p_1 and p_2 refer to the inlet and output pressures, respectively.

In addition, a high-pressure storage tank is used at the outlet of the electrolyzer in which the pressure is evaluated as

$$P_{ht} = n_{ht}\left(\frac{R\times T}{V_{ht}}\right) \quad (6)$$

Where n_{ht}, R, $T$and V_{ht}denote the gas number of moles, the gas constant, the inlet gas temperature and the volume of the hydrogen tank, respectively.

An autonomy parameter is also considered in HOMER expressing the ratio of the energy capacity of the hydrogen tank divided by the average primary electric load (kWh/day) as following:

$$A_{\text{h,tank}} = \frac{Y_{h,\text{tank}}\text{LHV}_{H_2}(24h/d)}{L_{prim,ave}(3.6MJ/kWh)} \quad (7)$$

Here, $Y_{h,\text{tank}}$ is the capacity of the hydrogen tank (kg), LHV_{H_2}defines the Lower Heating Value of hydrogen (120 MJ/kg) and $L_{prim,ave}$ is average primary load (kWh/d).

3.6 PV model

To supply the HRFS, a PV array is introduced to feed power to the Proton Exchange Membrane electrolyzer. In the HOMER modelling, the PV power system output is expressed with the following equation:

$$P_{PV} = F_{PV}C_{PV}\frac{G_T}{G_{T,STC}} \quad (8)$$

Here, F_{PV} is the photovoltaic derating factor, C_{PV} is the rated capacity of the PV array (kW); G_T is the global solar radiation incident on the surface of the PV panel in (W/m^2); and $G_{T,STC}$ is the incident radiation at standard test conditions fixed to be 1000 W/m^2.

Table 1
Technical and economic data details corresponding to each component of the hydrogen refuelling station (Gökçek and Kale, 2018a; Akhtari and Baneshi, 2019; Duman and Güler 2018)

Component description	Specifications
PV Module	
Model	Peimar SG370M
Panel type	Flat Plate
Type of Cell	Mono-crystalline Silicon
Rated Capacity (W)	370
Open Circuit Voltage (V)	48.93
Maximum Power Voltage (V)	40.1
Short Circuit Current (A)	9.81
Maximum Power Current (A)	9.23
Temperature Coefficient (%/°C)	-0.40
Nominal Operating cell Temperature (°C)	25
Efficiency (%)	19.1
Derating factor (%)	88
Ground reflectance (%)	20
Protection class against electric shock	Class II
Capital Cost ($/kW)	640
Replacement cost ($/kW)	640
Operation and maintenance costs ($/kW)	10.00
Lifetime (years)	30
Wind turbine	
Model	Enercon E-53 (800 kW)
Rated capacity (kW)	800
Hub height (m)	73
Cut-in wind speed (m/s)	3.0
Rated wind speed (m/s)	12.0
Cut-out wind speed (m/s)	34.0
Survival wind speed (m/s)	59.5
Rotor diameter (m)	52.9
Rotor swept area (m^2)	2,198
Number of blades	3
Capital Cost ($/kW)	1,000
Replacement cost ($/kW)	1,000
Operation and maintenance costs ($/kW)	12
Lifetime (years)	30
Batteries	
Model	Generic 1kWh Lead Acid
Nominal Voltage (V)	12
Nominal Capacity (kWh)	1
Maximum Capacity (Ah)	83.4
Capacity ratio	0.403
Rate constant (1/h)	0.827
Roundtrip efficiency (%)	80
Minimum State of Charge (%)	40
Maximum Discharge Current (Ah)	24.3
Maximum Charge Current (Ah)	16.7
Maximum charge rate (A/Ah)	1
Capital Cost ($/kWh)	110
Replacement cost ($/kW)	100
Operation and maintenance costs ($/year)	10
Life time (years)	10
Lifetime Throughput (kWh)	800
Converter	
Model	Generic
Efficiency (%)	95
Relative capacity (%)	100
Capital Cost ($/kW)	300
Replacement cost ($/kW)	300
Operation and maintenance costs ($/year)	0
Life time (years)	20

Table 1
Technical and economic data details corresponding to each component of the hydrogen refuelling station (Gökçek and Kale, 2018a ; Akhtari & Baneshi, 2019 ; Duman and Güler 2018) ….*Continued*

Component description	Specifications
Electrolyzer	
Model	Generic
Type	PEM electrolyzer
Efficiency (%)	85
Capital Cost ($/kW)	1,000
Replacement cost ($/kW)	1,000
Operation and maintenance costs ($/year)	20
Life time (years)	15
Hydrogen Storage Tank	
Capital Cost ($/kW)	1,148
Replacement cost ($/kW)	1,014
Operation and maintenance costs ($/year)	3
Life time (years)	15
Compressor	
Capital Cost ($/kW)	2,500
Replacement cost ($/kW)	2,500
Operation and maintenance costs ($/year)	50
Life time (years)	10
Dispenser	
Capital Cost ($/kW)	54,000
Replacement cost ($/kW)	54,000
Operation and maintenance costs ($/year)	170
Life time (years)	10

3.7 Battery storage and converters

To avoid problems of intermittency of energy when renewable systems cannot serve the electrical and hydrogen load, a back-up system with battery storage is highly needed. In fact, when an excess energy is available from electricity generation by Photovoltaic or wind turbine system, the battery stores it until the full charge and can supply the system and compensate the power lack when required. Hence, generic 12-V lead acid batteries with 1 kWh of energy storage are chosen in the current investigation. Another compulsory system is the converter allowing to sustain energy between AC and DC bus involved in scenarios 1 and 2 with a rectifier and inverter of 95% of efficiencies.

3. 8 H_2 dispenser and cooling process

As aforementioned, the hydrogen gas is firstly compressed in the compressor at about 350-700 bars pressure to be suitable for use as a fuel. The compressed H_2 gas is then distributed via a dispenser with 350 or 700 bar nozzles. In this context, a high-pressure hydrogen gas dispenser of Type B70 specially designed for specific pressure is chosen, creating an optimal filling environment with compact design and an operability that enables installation in limited space. Besides, the Type B70 model is able of dispensing hydrogen at a temperature of -20 C which is compulsory as the H_2 temperature rises during expansion, which requires a pre-cooling process to safely dispense the fuel to the hydrogen car. In addition, to enable the cooling of the hydrogen gas reaching this temperature − 20 °C, the energy consumption is fixed at 0.18 kWh/kg H_2 (Nistor *et al.* 2016) while the cooling capacity value is taken to be 0.72kW. with a hydrogen flow rate of 1.5g/s. (Ayodele *et al.* 2021, Elgowainy *et al.* 2017). It is worth noting that similarly to the compressor, the electrical energy for the cooling process is included in the electrical load when simulating with HOMER.

3.9 Financial modelling

The Hybrid Optimization of Multiple Energy Resources (HOMER) software is utilized in the financial study allowing to navigate the complexity that occurs in the refuelling stations in terms of cost effectiveness and finally lead to a reliable hybrid standalone system. The main financial viability is based on computing the net present cost (NPC), the levelized cost of energy (LCOE) and the levelized cost of hydrogen production (LCOH) that we intend to explain in the following subsections. Further technical and economic details and input data of HOMER are tabulated in Table 1.

3.10 Levelized cost of energy (LCOE)

The Levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net current generation cost over the useful life of the HRFS considered to be 25 years. It is used for investment planning and consistently comparing different power generation methods. It thus represents the average revenue per unit of generated electricity required to recover the cost and operating of the HRFS during the expected economic life and duty cycle. The input to LCOE is selected by the estimator and computed by HOMER as given:

$$LCOE = \frac{C_{ann,tot}}{E_{load,served}} \quad (9)$$

The LCOE is hence obtained by dividing the total annual cost of the hybrid system components $C_{ann,tot}$ ($/yr) by the total electrical load served $E_{load,served}$ (kWh/yr).

3.11 Levelized Cost of Hydrogen (LCOH)

HOMER computes the LCOH by dividing the difference between the total annualized cost and the annual electricity cost with the total annual hydrogen production as following:

$$LCOH = \frac{C_{annualized} - C_{elec}}{M_{hydrogen}} \quad (10)$$

Where $C_{annualized}$ is the total annualized capital cost of the refuelling station (\$/yr) involving the capital, replacement and operation and maintenance costs for the whole HRFS, C_{elec} is the revenue from annualized electricity sale (\$/yr) and $M_{hydrogen}$ the mass of annual hydrogen produced (kg/year).

3.12 Net Present Cost (NPC) calculation

When making a capital investment, economic accounting is necessary to determine whether the investment can be recovered. A very useful financial tool that HOMER optimizer incorporates is estimating the Net Present Cost of the project by making the difference between the present value of all expenses and the present value of all revenues attained during the lifetime of the proposed hybrid system, where the Total Net Present Cost is calculated as following:

$$NPC = \frac{C_{ann,tot}}{CRF} \quad (11)$$

Where $C_{ann,tot}$ denotes the total annualized cost (\$/yr), and CRF is the capital recovery factor which is evaluated in HOMER as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

Here n is the project lifetime (year) and i expresses the annual real discount rate (%) taken to be i=3.92% with an inflation rate supposed to be 2%.

4. Results and discussion

4.1 Technical and economic inputs

The hydrogen refuelling station is primarily designed with the various components incorporated in the hybrid system, namely the electric and hydrogen load, the PV panels, the wind turbine, converters, the batteries, the compressor, the hydrogen tank, and the dispenser. The input data of HOMER model are also implemented, and hourly meteorological data are considered in the optimization methodology and simulation. The technical and economic details relative to the system components utilized in the HOMER modelling are listed in Table 1.

Considering the multiple HRFS renewable components, the optimization process is performed in HOMER by considering the input parameters of geographic data with the corresponding solar and wind potentials. An optimal combination is then proposed by the software after large number of hourly simulations where HOMER models all possible HRFS combinations. The software in fact, proposes the optimal architecture of the HRFS meeting the load demand by sorting the NPC from lowest value to highest one relatively to the system components chosen and their corresponding inputs. In fact, for the optimization process, the Optimizer Settings section describes an optimization page that contains inputs affecting how the numerical optimization algorithm operates. This process of the HOMER Optimizer can be illustrated as following:

- HOMER firstly performs one optimization for each combination of Search Space variables. HOMER also runs an optimization for each system category if the "Optimize category winners?" is selected. This option limits the number of simulations for each optimization.
- HOMER predicts the maximum relative precision of decision variables allowed for convergence. At least N architectures must be closer than this from the best system, where N is the number of dimensions in the optimization. Then, distance is computed as a fraction of the total range specified for each decision variable.
- The maximum relative error in net present cost (NPC) required for convergence is calculated. The average NPC of the N systems closest to the best system must be within the specified fraction of the best system's NPC, where N is the number of dimensions in the optimization. This input is interpreted as a fraction of NPC.
- The Focus factor is considered allowing to control how evenly HOMER covers the optimization space with points (where each point is a system configuration). In this study the focus factor value is taken to be 50 allowing rapid results and better iterative and design procedure. A high focus factor concentrates points near existing points with a low NPC, whereas a low focus factor covers the space more evenly.
- Run additional optimizations with and without each component in the HRFS; if this is not selected, only the overall winner is optimized, and category winners may not be good. Meanwhile, if the Base Case is selected, the Optimizer performs a single extra simulation with these Search Space values in addition to the optimization.

On another hand, Regarding the validity of the HOMER model, the software has been widely used and validated by numerous studies, both numerically and experimentally. Several validation studies have demonstrated the capability of HOMER and its use in research projects, while allowing the programmer to compare various design architectures on the basis of their technical and financial merits (Chouaib *et al.* 2017, Alsafasfeh 2015, Barakat *et al.* 2016, Çetinbaş *et al.* 2019, Alshammari *et al.* 2018, Hassane *et al.* 2022, Khamharnphol *et al.* 2023, Diyoke *et al.* 2023, Mahmoudi *et al.* 2023, Ariae *et al.* 2019, Barakat *et al.* 2022). Additionally, HOMER has been validated against multiple software and techniques, as for example in the study of Milosavljević *et al.* 2022. Likewise, one can also refer to the investigation of Mokheimer *et al.* 2015 who used a mathematical code model based on MATLAB to simulate and optimize a hybrid system with different configuration and then validated the code against HOMER software. The validation gave good agreement with errors within 1% for all computed results with respect to HOMER predictions. In addition, for better optimization, the NREL firstly recommend simulating and performing the integrated hybrid system with HOMER and then proceed to other software like HYBRID2 (Ayop *et al.* 2018). Moreover, despite, there are various software tools that are available for modelling and optimizing renewable energy systems in the market (Bartolucci *et al.* 2023; Zhao *et al.* 2023; Güven and Samy 2022; Samy *et al.* 2018; Samy and Barakat 2019; Samy *et al.* 2019, Narayanan 2017, Zwalnan *et al.* 2021; Missoum and Loukarfi, 2021), the HOMER remains one of the most popular tools for sizing of the integrated system.

4.2 Optimized HRFS and Financial assessment

In this section, we present the HOMER simulation results corresponding to the HRFS at the 20 sites investigated obtained after optimization process. Furthermore, the financial analysis in HOMER simulation is presented in terms of NPC, LCOE and LCOH. The optimization results and the best techno-economic combinations according to all three scenarios at the French cities are listed in Table 2. Note that the value of renewable

Table 2
Optimization results of the HRFS according to the selected twenty cities with the relative H_2 generation for the 3 scenarios

Index	City	Scenario	PV	Wind Turbine (Nos)	Battery (Nos)	Electrolyzer (kW)	Hydrogen tank (kg)	Converter (kW)	Annual Hydrogen production (kg/year)	NPC ($)	Levelized cost of Energy (LCOE) ($/kWh)	Levelized cost of hydrogen production (LCOH) ($/kg)
C1	Paris	S1	370	1	47	100	100	24.1	4,109	1.57M	0.626	23.8
		S2	-	1	93	100	100	47.1	4,194	1.32M	0.525	20.0
		S3	343	-	503	200	100	-	4,181	1.06M	0.425	16.1
C2	Lille	S1	370	1	38	100	100	24.2	4,197	1.29M	0.625	23.8
		S2	-	1	81	100	100	45.2	4,182	1.31M	0.523	19.9
		S3	346	-	510	200	100	-	4,171	1.07M	0.426	16.2
C3	Luxembourg	S1	370	1	46	100	100	24.6	4,198	1.57M	0.626	23.8
		S2	-	1	93	100	100	47.1	4,194	1.32M	0.525	20.0
		S3	328	-	500	200	100	-	4,183	1.05M	0.419	15.9
C4	Cherbourg	S1	370	1	34	100	100	24.0	4,197	1.57M	0.625	23.7
		S2	-	1	82	100	100	47.9	4,195	1.32M	0.525	19.9
		S3	347	-	511	200	100	-	4,177	1.07M	0.428	16.3
C5	Saint-Lô	S1	370	1	33	100	100	23.9	4,197	1.57M	0.624	23.7
		S2	-	1	73	100	100	44.4	4,191	1.31M	0.522	19.9
		S3	342	-	507	200	100	-	4,174	1.07M	0.427	16.2
C6	Le Mans	S1	370	1	53	100	100	25.0	4,197	1.58M	0.628	23.9
		S2	-	1	125	100	100	46.7	4,192	1.33M	0.530	20.1
		S3	372	-	504	200	100	-	4,179	1.09M	0.435	16.5
C7	Sarreguemines	S1	370	1	55	100	100	25.7	4,198	1.58M	0.628	23.9
		S2	-	1	123	100	100	48.7	4,283	1.52M	0.607	22.6
		S3	339	-	485	200	200	-	4,185	1.05M	0.420	15.9
C8	Auxerre	S1	370	1	51	100	100	24.3	4,197	1.58M	0.627	23.8
		S2	-	1	107	100	100	48.0	4,195	1.32M	0.527	20.0
		S3	338	-	499	200	100	-	4,182	1.06M	0.423	16.1
C9	Vannes	S1	370	1	38	100	100	24.0	4,197	1.57M	0.625	23.8
		S2	-	1	75	100	100	47.1	4,196	1.31M	0.522	19.9
		S3	343	-	503	200	100	-	4,181	1.06M	0.425	23.9
C10	Dole	S1	370	1	65	100	100	25.4	4,198	1.58M	0.630	23.9
		S2	-	2	114	100	100	47.5	4,193	2.23M	0.888	33.7
		S3	333	-	478	200	100	-	4,179	1.05M	0.418	15.9
C11	La Rochelle	S1	370	1	43	100	100	23.8	4,197	1.57M	0.626	23.8
		S2	-	2	55	100	100	43.5	4,174	2.2M	0.876	33.5
		S3	345	-	499	200	100	-	4,178	1.07M	0.427	16.2

Table 2
Optimization results of the HRFS according to the selected twenty cities with the relative H_2 generation for the 3 scenarios (***Continued***)

Index	City	Scenario	PV	Wind Turbine (Nos)	Battery (Nos)	Electrolyzer (kW)	Hydrogen tank (kg)	Converter (kW)	Annual Hydrogen production (kg/year)	NPC ($)	Levelized cost of Energy (LCOE) ($/kWh)	Levelized cost of hydrogen production (LCOH) ($/kg)
C12	Clermont-Ferrand	S1	370	1	81	100	100	24.8	4,197	1.59M	0.633	24
		S2	-	2	145	100	100	47.4	4,192	2.24M	0.892	33.9
		S3	345	-	486	200	100	-	4,182	1.06M	0.424	16.1
C13	Aurillac	S1	370	1	65	100	100	23.9	4,197	1.58M	0.630	23.9
		S2	-	1	174	100	200	48.5	4,244	1.54M	0.615	23.1
		S3	321	-	483	200	100	-	4,197	1.04M	0.417	15.9
C14	Grenoble	S1	370	1	197	100	100	24.9	4,196	1.65M	0.654	24.8
		S2	-	9	219	100	400	49	4,138	9.15M	3.65	140
		S3	324	-	472	200	100	-	4,177	1.04M	0.415	15.8
C15	Chambery	S1	370	1	178	100	100	24.3	4,197	1.63M	0.650	24.6
		S2	-	7	207	100	200	48.6	4,150	6.96M	2.77	106
		S3	320	-	469	200	100	-	4,181	1.04M	0.414	15.7
C16	Montpellier	S1	370	1	65	100	100	23.9	4,197	1.58M	0.630	23.9
		S2	-	2	109	100	100	45.7	4,192	2.22M	0.886	33.7
		S3	419	-	434	100	100	-	4,171	925,653	0.370	14.1
C17	Marseille	S1	370	1	43	100	100	24.2	4,197	1.57M	0.626	23.8
		S2	-	1	104	100	100	46.1	4,192	1.32M	0.527	20.0
		S3	366	-	437	100	100	-	4,171	886,464	0.354	13.5
C18	Lyon	S1	370	1	78	100	100	23.9	4,197	1.59M	0.632	24
		S2	-	2	134	100	100	47.7	4,192	2.23M	0.891	33.8
		S3	321	-	476	200	100	-	4,177	1.04M	0.415	15.8
C19	Toulouse	S1	370	1	81	100	100	24.8	4,197	1.59M	0.633	24
		S2	-	2	138	100	100	47.1	4,190	2.24M	0.891	33.9
		S3	336	-	475	200	100	-	4,176	1.05M	0.421	16.0
C20	Pau	S1	370	1	127	100	100	24.1	4,197	1.61M	0.641	24.3
		S2	-	3	148	100	400	48.7	4,160	3.72M	1.48	56.8
		S3	365	-	480	200	100	-	4,177	1.08M	0.430	16.4

fraction defined as the fraction of the energy delivered to the load that originated from renewable power sources, is 100% in the current study for all HRFS data as the hydrogen station is fully powered with renewable energy sources.

For better understanding, we intent to discuss the results illustrated in Table 2 related to variation of the net present cost (NPC) according to the three scenarios under consideration relatively to the twenty French cities. As observed in the Table 2, the second scenario involving solely the wind turbine and battery bank seems to be the costliest according to all cities. Conversely, the PV panels with battery charge (Scenario 3) is likely to be the least costing among the other scenarios in terms of NPC for the hydrogen based refuelling station in France. Moreover, the NPC relative to the third scenario based only on PV panels seem to be more sensitive to site location with a value varying between $886,464 (C17, Marseille) and $1,090,000 (C6, Le Mans). This variation of NPC for Scenario 3 (PV-Battery) from one city to another may be due to the difference between the cities in terms of abondance of solar energy yield during the year in the French country possessing a large area. In fact, the lower NPC value obtained in Marseille city (C17) seems to be reasonable as it is situated in a Mediterranean coastal region and located at the Southern French country where more pronounced solar sources are available during the year. Besides, for the first and third scenarios, the NPC for the twenty cities are relatively close. An average NPC value of $1,561,429 and $1,038,117 are obtained for the first and second architectures while a higher net present cost of $2,522,727 is predicted for the second combination according to all sites considered. Nevertheless, this higher cost for the scenario based on wind turbine may be no longer a weakness. In fact, according to NREL and the findings described by Wiser *et al.* 2021 in the "Nature Energy" journal, the experts are expecting cost drops of nearly 17%-35% by 2035 and anticipating a reduction of 37%-49% by 2050, driven by lower capital and operating costs, the bigger and more efficient turbines, and other technological and commercial advancements. Hence, if we consider an expected reduction of 35%, the average NPC would be $1,639,773 for scenario 2 within 2035, which will be a competitive cost scenario for the HRFS in France in the near future.

On another hand, in terms of cost of energy and hydrogen productions, the comparison between the three cases for the twenty cities in terms of LCOE and LCOH listed in Table 2 demonstrates a lower levelized cost of energy and levelized cost of hydrogen for the third scenario with photovoltaic panels and battery charge components. Indeed, the lower results corresponding to levelized cost of energy and hydrogen production are in Marseille city (C17) with LCOE=$0.354 /kWh and a LCOH=$13.5/kg for the third scenario among both remaining architectures investigated. Compared to the first and second architectures, average values of LCOE=$ 0.41665 /kWh and a LCOH=$ 15.835/kg are obtained for the third scenario, while computations lead to average data of LCOE=$ 0.63095 /kWh and a LCOH=$ 23.96 /kg for configuration 1 and LCOE=$ 0.9586/kWh and a LCOH=$ 36.535 /kg for the second investigated scenario. For the first combination, it is observed that the lowest LCOE and LCOH are obtained for Saint-Lô (C5) city with $ 0.624 /kWh and $23.7 /kg meaning that such city is considered as good location choice in terms of achieving the hybrid profitability through reduced mains power use, and lower consumption cost when dealing with Hydrogen refuelling station establishment. It is worth noting, that a maximum levelized cost of energy and hydrogen is found in Grenoble (C14) city for both first and second scenarios with values of (LCOE=$0.654/kWh, LCOH=$24.8/kg) and (LCOE=$3.65/kWh, LCOH=$140/kg), respectively. These two maxima obtained for scenarios 1 and 2 seem to be in accordance with the greatest NPC obtained for Grenoble city (C14) (NPC= $1.65M). Accordingly, minimum values are also observed for Marseille city (C17) with LCOE=$ 0.354/kWh and a LCOH=$ 13.5 /kg in conformity with the minimum value of NPC value of $886,464 with respect to the third scenario. Among all scenarios adopted, the third scenario describing the hybrid refuelling station powered by Photovoltaic power seems to be the least costing when compared to remaining scenarios when only wind turbine system is used (configuration 2) or involved with PV system (configuration 1) and this for all the sites considered. In contrast, the scenario 2 when wind power and battery bank components are utilized for HRFS energy feeding is observed to be the most expensive system with respect to remaining configurations. One can conclude that the third scenario can be considered as "winner scenario" in terms of reducing the hydrogen production and power.

It is also expected that the outputs of the wind turbines and PV panels are primarily dependent on the local wind speed of the French site where the HRFS are installed. The higher the local solar radiation or wind speed sources are available, the higher the electricity and hydrogen are accordingly produced.

To demonstrate the capability of the hydrogen refuelling model presented in this study, the current computations are listed and compared with those available in literature in Table 3. The results are presented in terms of the LCOH for various power technologies scenarios, several hydrogen production techniques and different load consumption. It is worth noting that the conversion from Euro to USD currency ($) is based on the exchange rate of September 2022 (1.00 Euro = 1.00 USD). Regarding the hydrogen produced from electrolysis process adopted in the current study, the LCOH in literature is varying between from $5.18/kg to $15.7/kg depending on the adopted technologies which is in fair accordance with the current results ranging especially for the "winner scenario" (Scenario 3) where the LCOH varies between $13.5 /kg to $16.5 /kg. It is observed that the current LCOH computations for the third scenario based on PV panels are acceptable when considering the comparison of the cost of hydrogen production obtained in literature for instance with water electrolysis. In addition, this current data is in accordance with the average hydrogen cost in Europe predicted to be in the range 2 EUR/kg ($2/kg) to more than 14 EUR/kg ($14/kg) in 2023.

For the first and second combinations, the cost is further reducing each year and hence the renewable components price are yearly updated which will certainly reduce the hydrogen producing cost in the foreseeable future. Additionally, these falling costs of renewable energy technologies makes the HRFS based on clean power a viable option where it is used in the French country to displace the gasoline burning as long as that gasoline is estimated at the international selling price.

Besides the global electricity generation is exhibiting evolution and transition in its shift from fossil-fuel domination in 2015 to almost 98% renewables by 2040, and to zero greenhouse gas emissions by 2050. Besides, for the better LCOH values obtained for solely PV based scenario is due to that PV technologies enjoy a great advantage due its versatility, with cost reductions projected to increase by 1% in 2015, 32% in 2030, and up to 76% in 2050 (Martínez de León 2023). Contrarily, scenario 2 powered with wind turbines provided the main source of renewable energy during the early part of the transition and its share of electricity supply is estimated to rise to 42% by 2030. While the green hydrogen production with wind turbines production will steadily decline.

Table 3
Current results of levelized cost hydrogen (LCOH) compared with that available in literature for hydrogen refuelling station.

Geographic location	Source of hydrogen	Daily hydrogen load (kg/day)	System technologies	LCOH ($/kg)	References	Year
France (20 cities)	Water electrolysis Water electrolysis Water electrolysis	125	PV/Wind//Battery Wind//Battery PV/Battery	Scenario 1: $ 23.7 /kg to $24.8/kg Scenario 2: $19.9 /kg to $140 /kg Scenario 3: $13.5 /kg to $16.5 /kg	Current study	2023
South Africa (7 cities)	Water electrolysis	125	Wind/Battery systems	$6.34 /kg to $8.97 /kg	Ayodele *et al.* (2021)	2021
Turkey (island of Gökçeada)	Water electrolysis Water electrolysis	125	Wind/PV/Battery Wind/battery systems	$ 8.92/kg $ 11.08/kg	Gökçek and Kale (2018b)	2018
Sweden	Water electrolysis Water electrolysis	1600	V112 wind turbine V82 wind turbine	$5.18/kg to $7.25/kg $6.52/kg to $9.62 /kg	Siyal *et al.* (2015)	2015
USA (Irvine, California)	Water electrolysis Water electrolysis	25	PV/PEMFC Wind/PEMFC	$ 9.14 /kg $ 6.71 /kg	Zhao and Brouwer (2015)	2015
Norway	Water electrolysis	60	Hydro/Grid	EUR 9.2/kg ($9.2/kg) to EUR 15.7/kg ($15.7/kg)	Ulleberg, and Hancke (2020)	2020
Italy	Water electrolysis	200	PV/Grid	EUR 9.29/kg ($9.29/kg)	Minutillo *et al.* (2021a)	2021
Italy	Water electrolysis	450	PV/Grid	EUR 7.92/kg ($7.92/kg)	Perna *et a*l. (2022)	2022
Italy	Ammonia	200	PEMFC	EUR 7.35/kg ($7.35/kg)	Perna *et al.* (2020)	2020
Italy	Ammonia	100	SOFC	EUR 6.84/kg ($6.84/kg) to EUR 9.78/kg ($9.78/kg)	Minutillo *et al.* (2021b)	2021
Italy	Ammonia	450	PEMFC SOFC	EUR 6.28/kg ($6.28/kg) EUR 6.89/kg ($6.89/kg)	Perna *et al.* (2022)	2022
Italy	Biogas	100	Grid	EUR 5.0/kg ($5.0/kg) to EUR 7.2/kg ($7.2/kg)	Marcoberardino *et al.* (2018)	2018
Italy	Biogas	100	SOFC	EUR 11.23 /kg ($11.23/kg)	Perna *et al.* (2019)	2019
Italy	Biogas	450	SOFC	EUR 7.25 /kg ($7.25/kg)	Perna *et al.* (2022)	2022

Note: The conversion from Euro to USD currency is based on the exchange rate of September 2022 (1.00 Euro = 1.00 USD)

Concerning the difference of hydrogen cost between multiple cities, some components like the electrolyser and hydrogen storage needs attention when considering LCOH, as they are another significant part of initial investment. As solar

PV has a strong seasonal pattern, whereas wind is intermittent, the first scenario combining PV panels and wind turbines has the benefit of lowering the capacity requirement of storage and electrolysis process. Additionally, it will be interesting to concentrate on strengthening the overall power of the back-up battery bank while trying to reduce its cost to stabilize the supply of electricity to the electrolyzer. This remains a topic of research study for future investigation. Another alternative of reducing the production cost of the green hydrogen is the reduction of the overall initial investments, including wind turbines, the PV arrays, the PEM electrolyzer, and storage system. This can be applied by expanding the production scale as the total cost can be pressed down along with its large size, and therefore the LCOE and LCOH.

4.3 Typical daily stored hydrogen

For the sake of better readability, Fig. 9 displays a surface drawing of the stored hydrogen in the tank (in kg) during a typical winter day (1st January) and typical summer day (1st July) for the three combinations considered and relatively to the twenty French cities investigated. For the three scenarios, the summer days at the twenty cities seem to generate a more significant quantity stored hydrogen that may be multiplied by ten times the quantity of hydrogen in winter days and reaches the hundred kg per hour which is not the case for colder days in winter. In fact, while the wind yield is more pronounced in winter, the contribution of PV panels with better performance in hotter days may strengthen the energy output and hence leads

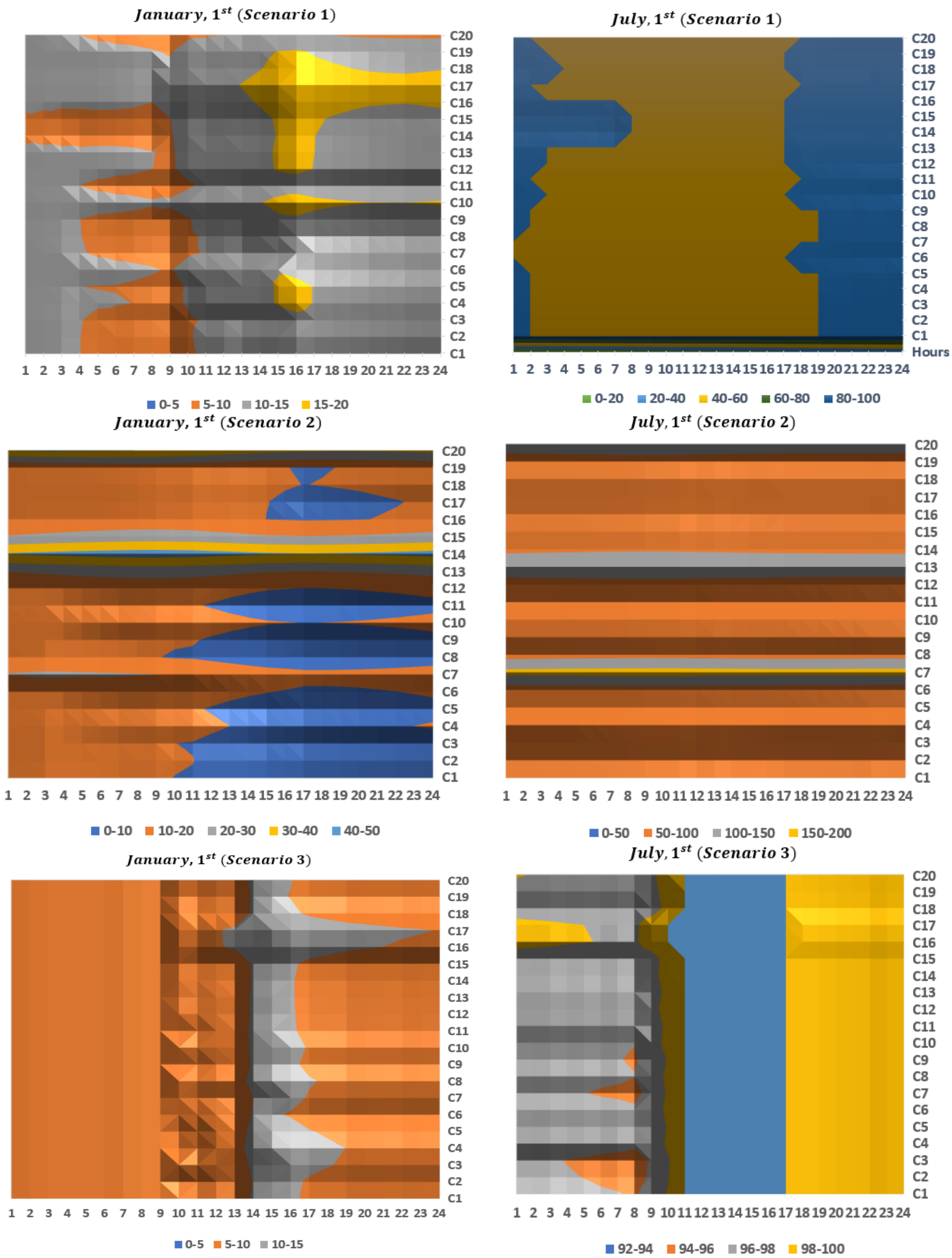


Fig. 9. Daily stored hydrogen in the tank (in kg) during a typical winter day (1st January) and typical summer day (1st July) for the three scenarios investigated and according to the twenty French cities under consideration.

to significant hydrogen production and storage. It is noteworthy that for scenario 1 and 2, Enercon wind turbines contribute to a significant portion of electricity feeding and hence hydrogen production during the autumn and winter seasons due to relatively high wind speeds in each site which explain the difference pattern between the winter and summer typical sketch of daily stored hydrogen in the tank for the different scenarios.

4.4 CO_2 mitigation and environmental contribution

In this part, we attempt to discuss the impact of the HRFS on the abatement of the amounts of carbon dioxide (CO_2) spewing into the atmosphere that are derived from the combustion of petrol (Gasoline). In Table 4 are listed the results relative to all cities and for the three scenarios in terms of annual gasoline reduction with respect to the corresponding CO_2 reduction amount per annum. According to Eq. 13 describing the combustion of Petrol (Gasoline), 1 kg of Petrol combustion will produce 3.088 kg of carbon dioxide CO_2 emissions to the atmosphere (Siyal *et al.* 2015).

$$2\,C_8H_{18} + 25\,O_2 \rightarrow 16\,CO_2 + 18\,H_2O + \text{energy} \quad (13)$$

As revealed from the table, an average amount within the 4.2 tons of gasoline can be replaced by almost 12.9 tons of carbon dioxide per year for each city with respect to the three scenarios investigated. Therefore, a total amount within 83 tons per annum of carbon dioxide could be mitigated and the hydrogen produced may replace a total amount of nearly 259 tons of gasoline per year when considering the sum of all the twenty French cities.

5. Conclusion

Techno-economic analysis of hydrogen refuelling stations installed in 20 different French cities is performed to promote the use of renewable energy instead of conventional power generation methods. This study is motivated by the fact that almost all existing HRFS in the French country are still off-site stations where the hydrogen is obtained from non-renewable sources, the current HRFS model is expected to satisfy the daily hydrogen fuelling of 25 cars fuelled with green hydrogen produced with renewable energy technologies. For this aim, three scenarios leading to 60 combinations are investigated: namely Scenario 1 consisting of a (PV-Wind-Battery) system, a Scenario 2 with (wind-Battery) technologies and a Scenario 3 with a (PV-Battery) system. The technical and financial details of the architectures obtained after HOMER optimization process leading to the best configuration for the twenty sites considered is presented and analyzed. The economic evaluation in HOMER simulation is presented in terms of NPC, LCOE and LCOH. With an average NPC value of $1,038,117 for the 20 cities, it is found that scenario 3 based on the solar PV technology is less costly while the scenario 2 where wind turbines are the main renewable power source with battery storage seems to be more expensive with an average NPC of $2,522,727 according to all French sites explored. Besides, the third combination is observed to be more sensitive to site location in terms of NPC with a least value obtained at Marseille

Table 4
Environmental impact in terms of yearly replaced gasoline amount versus the dioxide of carbon abatement for different French sites adopted.

Index	City	Replaced gasoline amount (tons/year)			Avoided CO_2 emission (tons/year)		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
C1	Paris	4,197	4,194	4,181	12,960.34	12,951.07	12,910.93
C2	Lille	4,197	4,182	4,171	12,960.34	12,914.02	12,880.05
C3	Luxembourg	4,198	4,186	4,183	12,963.42	12,926.37	12,917.10
C4	Cherbourg	4,197	4,195	4,177	12,960.34	12,954.16	12,898.58
C5	Saint-Lô	4,197	4,191	4,174	12,960.34	12,941.81	12,889.31
C6	Le Mans	4,197	4,192	4,185	12,960.34	12,944.9	12,923.28
C7	Sarreguemines	4,198	4,283	4,179	12,963.42	13,225.9	12,904.75
C8	Auxerre	4,197	4,195	4,182	12,960.34	12,954.16	12,914.02
C9	Vannes	4,197	4,196	4,181	12,960.34	12,957.25	12,910.93
C10	Dole	4,198	4,193	4,179	12,963.42	12,947.98	12,904.75
C11	La Rochelle	4,197	4,174	4,178	12,960.34	12,889.31	12,901.66
C12	Clermont-Ferrand	4,197	4,192	4,182	12,960.34	12,944.90	12,914.02
C13	Aurillac	4,197	4,244	4,197	12,960.34	13,105.47	12,960.34
C14	Grenoble	4,196	4,138	4,177	12,957.25	12,778.14	12,898.58
C15	Chambery	4,197	4,150	4,181	12,960.34	12,815.2	12,910.93
C16	Montpellier	4,197	4,192	4,171	12,960.34	12,944.9	12,880.05
C17	Marseille	4,197	4,192	4,177	12,960.34	12,944.9	12,898.58
C18	Lyon	4,197	4,195	4,177	12,960.34	12,954.16	12,898.58
C19	Toulouse	4,197	4,190	4,176	12,960.34	12,938.72	12,895.49
C20	Pau	4,197	4,160	4,171	12,960.34	12,846.08	12,880.05
	Average amount	4,195.55	4,179.4	4,178.95	12,955.86	12,905.99	12,904.6
	Total amount	83,911	83,588	83,579	259,117.2	258,119.7	258,092

city (C17) with the value NPC= $886,464 and a maximum one of $1,090,000 in Le Mans city (C6). Similarly, according to all cities, simulations reveal average values of LCOE=$ 0.9586/kWh and a LCOH=$ 36.535 /kg for the costliest configuration (second wind-based scenario), while computations lead to average LCOE=$ 0.63095 /kWh and a LCOH=$ 23.96 /kg for configuration 1 and LCOE=$ 0.41665 /kWh and a LCOH=$ 15.835/kg for the third investigated scenario. In the case of hydrogen production by electrolysis, comparison of the LCOH with literature for the twenty cities with 60 possible combinations (3 scenarios for each city) leads to a varying LCOH between $13.5 /kg to $16.5 /kg for the values relative to the "winner scenario" (Scenario 3) which is in fair agreement with data in literature depending on the implemented technologies.

In addition, the cash flow of the HRFS project is discussed for all cities showing similar pattern while exhibiting a positive trend and marking the salvage value of all optimized HRFS as it is profitable only after the 25 years project life. On another hand, comparison of stored hydrogen in the tank for winter and summer period reveals that hot seasons are manifested by further produced and stored hydrogen amount compared to colder seasons in all cities.

Regarding the environment contribution, the model of HRFS proposed herein leads to a mitigation amount of carbon dioxide of almost 83 tons that can be yearly reached and may replace a total amount of 259 tons per annum of gasoline when considering the twenty geographic sites investigated.

More inspiring is the fact that the renewable technologies continue to be widely used in the world, and cost reductions are progressing due to competition among businesses and the worldwide encouragement to reduce the carbon dioxide pollution caused by fuels. The collected HOMER modelling data from the current study provide valuable information for the technical and financial assessment for future applications of HRFS in the emerging transport technology in the French local environment. The study offers a valuable reference for policy makers and French investors that are foreseeing the industrial landscape for hydrogen energy production growth in transport sector. In addition, while the cost of green hydrogen production based on renewable sources remains still challenging and extremely depends on the geographic location, the need to invest in transport sector with refuelling stations infrastructure is then required. This investigation then reveals how essential it is to use renewable energies to produce clean hydrogen to feed vehicles which could be a viable French local fuel in terms of financial production costs and energy use, when compared to fossil fuel sources.

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Nomenclature

$A_{h,tank}$	Autonomy parameter.
$C_{ann,tot}$	Total annual cost ($/yr)
Cp	Power Coefficient of the wind turbine.
CO_2	Carbon dioxide.
C_{p,H_2}	Specific heat of hydrogen (14.304 kJ/kg K)
C_{PV}	Rated Capacity of the PV array (kW)
C_{elec}	Revenue from annualized electricity sale ($/yr)
CRF	Capital Recovery Factor
E_{served}	Total electrical load served (kWh/yr)
F_{PV}	Photovoltaic derating factor.
G_T	Global solar radiation incident (W/m^2)
$G_{T,STC}$	Incident radiation at standard test conditions ($G_{T,STC}$ = 1000 W/m^2)
HOMER	Hybrid Optimization Model for Electric Renewable
HRFS	Hydrogen Refuelling Station
H_2	Hydrogen
i	Annual real discount rate (%)
LHV_{H_2}	Lower Heating Value of hydrogen (LHV_{H_2}= 120 MJ/kg).
LCOE	Levelized Cost of Energy ($/kWh).
LCOH	Levelized Cost of Hydrogen ($/kg).
$L_{prim,ave}$	Average primary load (kWh/d).
$M_{hydrogen}$	Mass of annual hydrogen produced (kg/year).
m_c	gas flow rate (kg/s)
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost ($).
NREL	National Renewable Energy Laboratory
O_2	Oxygen.
OER	Oxygen Evolution Reaction
P_{comp}	Rated power of the compressor (W).
P_{wind}	Wind turbine output power (W)
P_{ht}	High-pressure of storage tank (W)
PEM	Polymer Membrane Electrolyzer
R	Gas constant (R=0.08206 L atm mol^{-1} K^{-1})
r	Isentropic exponent of hydrogen (r=1.4)
$Y_{h,tank}$	Capacity of the hydrogen tank (kg)
z_{hub}	Hub height (m)
z_{anem}	Anemometer height (m)

Greek symbols

η_c	Compressor efficiency.
α	Power law exponent
η_{ht}	Gas number of moles.
ρ	Density of the air (kg/m^3).
v_{hub}	Wind speed ratio at the hub height (m/s)
v_{anem}	Wind speed at anemometer height (m/s)

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