Evaluation of Energy Options for Island Communities: A Case Study on Ushant

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Abstract The island of Ushant, like many island communities, faces major energy challenges, exacerbated by climate change and dependence on fossil fuels. In this context, the design of sustainable energy solutions, reducing greenhouse gas emissions and ensuring reliable access to energy and maritime transport is essentiel. To achieve these goals, a sizing simulation tool based on Matlab Simulink has been developed. This tool integrates several renewable energy sources, including wind, tidal turbines and photovoltaic systems, as well as hydrogen production and storage.

The aim of this work is to model and evaluate different energy scenarios for the island, taking into account its specific energy demand and the needs of its maritime mobility. Taking into account both local grid and maritime mobility energy needs is one of the originality of this work. Four scenarios have been formulated. The first and second aim to achieve total energy autonomy for the island and its maritime mobility, using a hybrid hydrogen vessel for the first and a battery powered electric vessel for the second. The third scenario ensures the complete coverage of the island's electrical load, whereas the fourth scenario covers only 70%, maintaining dependence on fossil fuels for the remaining 30% and also for maritime mobility. In order to find the best trade-off between cost and environmental impact in finding a sustainable and economically viable energy solution, a cost (CAPEX) comparison is also proposed.

1 Introduction

Providing sustainable and reliable energy to islands is a significant challenge due to their geographical isolation. Their openness to tourism is balanced by their dependence on fossil fuels, revealing specific needs in terms of mobility and highlighting the fragility of their nearby ecosystems [1]. The presented work is intended to respond to this challenge by providing a feasible solution based on available and accessible energy resources [2]. The investigated solution is based on developing an integrated island and port energy systems exploiting renewable energies (RE) for electricity and hydrogen production. One of the objectives is to use hydrogen as an energy vector between production, local consumption and energy needs linked to maritime mobility. The study will be based on the case of the island of Ushant, an electrically isolated island located off the coast of Britanny in France. Section 2 presents the case study, and then the models used for the simulations are described in Section 3. Finally, the simulation results of several studied scenarios are presented and discussed in section 5.

2 Context of the Study

2.1 General specifications on the island of Ushant

Ushant is part of the Molène Archipelago, which is located near the Brittany Coast in France. It's the largest island in the Iroise Sea, with a surface area of 15.59 km^2. It currently depends on diesel generators to meet its electricity demand. The total electricity consumption on the island is

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estimated at around 7.1 GWh per year, equivalent to around 1,600 tonnes of diesel fuel [3]. Due to its geographical location, Ushant Island is not connected to the continental power grid and must generate its own energy. It relies on two main sources: a diesel-powered thermal plant with four production units with a total rated power of 4400 kW and photovoltaic installations with a rated power of 92 kW. Additionally, a lithium lion battery unit is implemented in the island with an energy capacity of 1 MWh. The ship deserving the island, Fromveur II, powered by a 3300 kW diesel engine, plays an important role in the island's daily transport system and is a key element in the study. It's energy consumption amounts to around 400 liters of diesel per hour [19]. The ships like Fromveur II make 1 to 2 round trip a day between Brest and Ushant (4 hours for a round trip). These round trip are the main parts of the island, accounts for a significant proportion of the island's maritime mobility energy demand. These ships are also responsible for supplying diesel fuel to the thermal power plant. The current solution is characterized by a dramatically high level of CO2 and pollutant emissions due the massive use of the Diesel Generators. The simplest solution to considerably reduce diesel consumption would be to connect Ushant Island to the national grid, but the estimated cost for this connection is around 70 million euros, a considerable expense for the local and national collectivities [4].

2.2 Ushant's renewable energy potential

The decision to exploit wind, tidal and solar energy on the island of Ushant in this work is based on an assessment of the renewable resources available in the region, as well as on the PHARES project [18]. The project presented in this paper aims to ensure Ushant's energy autonomy from renewable sources. The location of the island of Ushant is situated in a windy area (the wind speed average is higher than in the rest of France), making the wind resource particularly attractive. In addition, the Fromveur straight (sea passage between the Molène archipelago and the island of Ushant) is one of the french site where the strongest tidal currents in France are located, reinforcing the attractiveness of tidal power [6]. Although the solar potential of the island of Ushant is lower than the national average, the decision was taken to not add any additional solar installations as part of this global energy choice.

3 Modelling of hybrid renewable energy systems

In this section, the modeling of each element within the microgrid is addressed. The adopted approach focuses particularly on power flows, with a positive sign assigned to energy production and a negative sign associated with energy consumption. The simulation of the exchanges between the components is done using Matlab-Simulink tool.

3.1 Wind Turbine and Tidal Turbine

The implementation of the wind and the tidal turbines in the MATLAB Simulink is based on a power extraction strategy curve like show in Fig. 1 [6], which is based on the technical characteristics of existing turbines. This simple model gives directly the turbine power as a function of the wind or tidal velocity. The considered wind and tidal turbines are horizontal axis turbine.

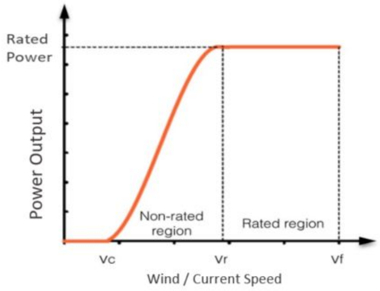

Fig. 1 Typical wind / tidal turbine power curve

3.2 Photovoltaic Panels

The PV installation used in this work is based on the MSX-83 module from SOLAREX, whose characteristics are given in [22]. The model used takes as input the ambient temperature and solar irradiance specific to the site studied. Maximum Power Point Tracking (MPPT) strategy is then used to optimize this output, ensuring that the panels operate at maximum efficiency by adjusting their operating point continuously in response to solar irradiation changes. On the basis of these parameters, the model generates the output power produced by the solar panels from a power VS irradiation curve as in [9].

3.3 Diesel Generators

On the island of Ushant, two electrical plants using diesel generators are used to supply power. The first uses two 1MW generators, while the second uses two 1.2MW generators. In this study, the focus is on the control strategy for these generators and on estimating fuel consumption. Diesel generators are considered to be perfectly controllable power sources and the diesel consumption is estimated from the typical specific fuel oil consumption (SFOC) curves given in [6] and show in Fig. 2. A 1.2 MW diesel generator is used first when demand is low, as it is more energy-efficient. As demand for electricity increases, the 2nd 1.2MW generator and the two 1MW generators are progressively started up to meet this increasing demand. This gradual activation is adopted to avoid the use of diesels at low power levels, due to their high consumption compared to high power levels, and therefore their bad efficiency [6].

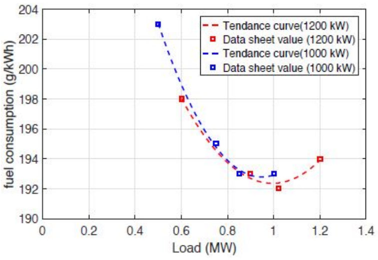

Fig. 2 Diesel consumption vs power

3.4 Storage systems

3.4.1 Battery Pack

The lithium-ion battery pack was modeled using the integrated Matlab Simulink® Battery block. It is important to note that the impact of temperature and ageing are not taken into account for this first order study [10].

3.4.2 Hydrogen Storage System

In recent years, hydrogen-based storage systems are becoming important for long-term storage due to their high energy capacity, very low self-discharge rate and the possibility to use hydrogen as fuel for mobility applications [11]. Proton exchange membrane (PEM) technology for fuel cells and electrolysis is particularly well adapted to renewable energy applications due to its high reactivity and lower degradation rate than other technologies, even in the presence of fluctuations [9].

- Fuel Cell : the model used is based on a proton exchange membrane fuel cell (PEMFC) curves integrated in Matlab Simulink. The model is detailed in [20].
  The stack temperature is assumed to be regulated and kept constant, eliminating the need to consider its impact on the fuel cell behavior. The hydrogen consumption of the fuel cell n_{H2FC} in mol/s is calculated using Faraday's law, which is related to the current i_{FC} flowing through the N_{CellFC} cells as shown in equation (1).

$$n_H 2FC = \frac{N_{CellFC} i_{FC}}{zF} \tag{1}$$

- Electrolyser : the electrolysis model used was designed on the basis of [12]. Similar to PEMFC the hydrogen consumption is calculated from the Faraday relationship and the temperature is assumed to be regulated and kept constant.
- Hydrogen Tank : in the reservoir, the ideal gas law will be used to determine the pressure variation in the reservoir [16].

$$P_{tank} = \frac{nRT}{V} \tag{2}$$

Where n is the molar mass of the gas, P_{tank} is the reservoir pressure, T is the the compressor discharge temperature, R is the perfect gas constant and V the reservoir volume. The hydrogen mass can be calculated using the convention of volumetric hydrogen flow in mass flow and then integrating the mass flow. The relationship for the pressure variation becomes

$$n_{tank} = P_0 + \frac{\dot{n}R}{V}dt \tag{3}$$

Where $\dot{n}$ is the hydrogen mass flow rate and P_0 is the hydrogen admission pressure in Pascal.

- Compressor : the compressor compresses the hydrogen output from the electrolysis unit. The model used calculates the power and consequently the energy consumed during the compression process which is taken into account. The model used is fully presented in [14].

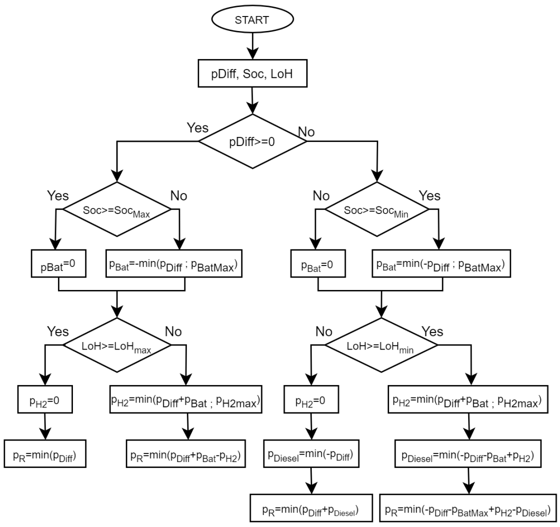

Fig. 3 Energy Management Strategy.

3.5 Energy Management Strategy

An energy management strategy is used to conduct these simulations, based on basic rules as illustrated in Fig. 3. This strategy takes into account several parameters, including the quantity of renewable energy generated, the island power demand, the battery's state of charge (Soc) and the quantity of hydrogen available in the tank (LoH). The difference between the power demand of electricity P_{Demand} and the renewable energy (RE) systems power production P_{RE} is defined by the power P_{Diff} which is defined as in (4)

$$P_{Diff} = P_{Demand} - P_{RE} \tag{4}$$

The energy strategy is based on a hierarchy of priorities for the use of different energy sources. Energy stored in the battery is prioritized for an efficient use, then hydrogen is used as an alternative energy source. In the event of increased demand or insufficient storage, diesel generators are activated, ensuring reliable response to consumer demand. When there is an excess of renewable energy unused, the strategy anticipates storing it in the battery pack or producing hydrogen. In case of the hydrogen tank and storage system are full, it's considered that the RE sources are controlled to not produce the energy excess. This strategy plays an important role in maximizing the use of renewable energy while minimizing dependence on diesels. It also offers the flexibility needed to balance energy production and demand, ensuring a reliable energy supply for the whole island.

4 Resource modeling and consumption curve

The simulation tool uses resource data as inputs (wind and tidal velocities, solar irradiation). These data have been collected from [6] and HOMER Pro software. A typical consumption curve corresponding to a statistical analysis of the consumption of the island from EDF-SEI [7] has been used for the island power versus time (black curve in figure 4). All these data used was extracted over a one-year period, with a time step of one hour between each data point.

5 Results and Comparative Analysis

In this study, various scenarios were explored to estimate the energy needs of the island and its maritime mobility. These scenarios were designed to analyse different potential solutions for the island of Ushant. The analysis will focus on several crucial aspects, including energy efficiency, investment costs, CO2 emissions, and the reliability of energy production. A simulation tool was developed in Matlab Simulink to analyze these scenarios using the sizing detailed in Tab. 1, models and systems presented in previous section.

Table 1 Caracteristics of the Hybrid System

Element	Parameters	Values
Wind Turbine	Rated Power (KW)	1000 (one unit)
	Cut-in speed (m/s)	3
	Rated Speed (m/s)	15
	Cut-off speed (m/s)	25
	Power coef MPPT	0.45
	Model	Bonus B54/1000
	Cost ($/kW)	4000 [13]
Tidal Turbine	Rated Power (KW)	500 (one unit)
	Cut-in speed (m/s)	1
	Rated Speed (m/s)	4
	Power coef MPPT	0.35
	Cost ($/kW)	4200 [13]
PV	Rated Power (KW)	92
	NOCT ($^\circ C$)	47
	Standard Operating Conditions	20°,$0.8 KW/m^2$,1m/s
	Model	MSX-83 SOLAREX
Diesel Generators	Total Rated Power (KW)	4400
	Model	2 Wartsila of 1.2 MW 2 Wartsila of 1 MW
Battery Pack	Rated voltage (V)	6600
	Rated Capacity (Ah)	1269 / 635
	Discharge/charge current (A)	606 / 303
	Rated Power (KW)	4001 / 2000
	Energy (KWh)	8375 / 4188
	Cost ($/kWh)	300 [13]
Electrolyser	Power(KW)	1100 / 600
	Current density (A/m2)	1
	Efficiency (%)	65
	Current (A)	300 / 150
	Cost ($/kW)	800 [13]
Fuel Cell	Power (KW)	1400 / 700
	Efficiency (%)	60
	Courant (A)	300 / 150
	Cost ($/kW)	3000 [13]
Load	Energy demand of Ushant Island (KWh)	7100

5.1 Scenarios Studied

For the island of Ushant, several scenarios are envisaged, as there are two types of energy demand: the first is the island's local electrical demand, and the second is the energy needed for the vessels operating the shuttle service to the continent. This ships currently uses fossil fuels, but the study in [5] shows that different scenarios are possible. Four scenarios were tested and detailed below.

5.1.1 First Scenario: 100% Renewable Energy with a Vessel supplied by the island ressources

The objective of this first scenario is to cover the totality of the island's electricity demand using renewable energy sources, and to ensure the total daily hydrogen needs of maritime mobility serving the island of Ushant. To achieve this objective, it is essential to satisfy the energy demand of the island of Ushant, which is around 7.1 GWh per year. In addition, it's necessary to produce all the ships hydrogen requirements, equivalent to around 353 kilograms per day. These hydrogen requirements have been estimated in previous work [5]. To produce this 353 kg of H2, 21.18 MWh/day are needed considering that about 60kWh is needed to produce 1kg of H2 [16], representing 8,49 GWh per year. A total of 15.5 GWH of electric energy is needed to cover the island's electricity demand and ensure all the daily hydrogen needs of maritime mobility serving the island of Ushant. To generate the required energy, a specific assessment considering the electricity quantity produced yearly by each unit of renewable energy systems (WT, TT, PV) is determined as detailed in Tab. 2. To ensure grid stability, a 4 MW/8 MWh battery pack is integrated, as well as a 1.4 MW fuel cell and a 1.1 MW electrolysis to produce hydrogen.

5.1.2 Second scenario: 100 % Renewable Energy with an Electric Vessel

The aim of this second scenario is to achieve total energy autonomy for the island of Ushant using renewable energy sources, while ensuring maritime mobility with an a battery powered vessel. In this case the vessel batteries will be charged by the island grid during docking. The option preferred is an electric vessel, while the other components and methodology stay similar to the previous scenario. According to [5], the vessel energy requirements are estimated at 5.8 MWh for a round trip, equivalent to an annual demand of 2.3 GWh. For an annual requirement of the island and its mobility of around 9.4GWh as show in Tab. 2. A battery pack, a fuel cell and an electrolysis unit are also integrated into the microgrid with the same capacity as the first scenario.

5.1.3 Third scenario: 100 % Renewable with a diesel vessel

The main aim of this scenario is to guarantee full coverage of the island's electricity demand, which is 7.1GWh, using a combination of renewable energies, while conserving the existing diesel vessel, which consumes around 1,300 liters for a round trip [5]. The required installation is detailed in Tab. 2.

5.1.4 Fourth scenario: : 70 % Renewable with a diesel vessel

The aim of the fourth scenario is to supply 70% of the island's energy consumption using just one 1 MW wind turbine, while the remaining 30% of the island's electrical load will be covered by the four existing diesel generators on Ushant. Its annual consumption is estimated at around 501 tonnes. The other elements and technology are similar to those of the third scenario. Mobility will be provided by the existing diesel vessel.

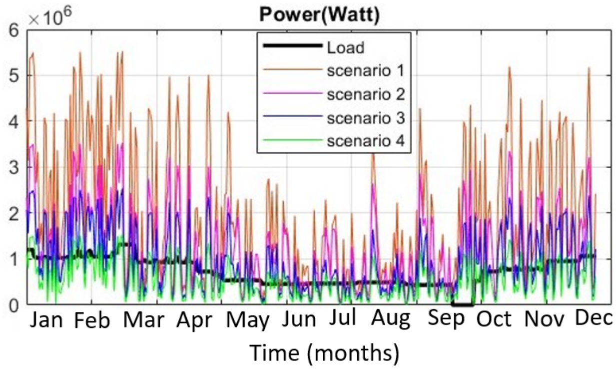

Fig. 4 Renewable Energy generated by the different scenarios / Power demanded by the island's electrical load

5.2 Scenario Analysis

Simulation results and the pros / cons of the different scenarios are presented in figures Fig. 4 and Tab. 2, and discussed below. The first scenario, offers the strategic advantage of ensuring total energy autonomy for the island of Ushant through renewable energy sources. This would have a significant positive impact on reducing greenhouse gas emissions, and the hybrid hydrogen boat offers attractive autonomy and rapid recharging time. It is essential to note that the scenario involving hydrogen production has a relatively low energy efficiency, placing it as the most energy-consuming scenario. As illustrated in Fig. 4, production exceeds the island's electricity demand. However, this scenario is characterized by a substantial infrastructure and investment requirements needed to implement this system. In the second scenario, the production of renewable energy is reduced, due to the superior efficiency of the the ship energy chain (the Power to Battery to Power Chain has a higher efficiency than the Power to Hydrogen to Power Chain). Although it satisfies sustainability objectives by minimizing greenhouse gas emissions but question remains in the ship battery sizing, aging and recycling cycles. And this scenario requires significant infrastructure to support the vessel's daily operations. The moderate investment cost of the third scenario reinforces its economic viability. But its dependence on fossil fuels for marine mobility limits its environmental benefits. The fourth scenario is distinguished by its significantly lower investment cost compared to the other three options. However, it is crucial to note that despite this financial saving, a substantial quantity of diesel is still required to cover 30% of the island's electrical load, in addition to the essential fuel to ensure mobility. This continued reliance on diesel results in high CO2 emissions and com-

Table 2 Cons / Pros of each scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Number of Wind Turbines	4 units	2 units	1 unit	1 unit
Number of Tidal Turbines	2 units	3 units	1 unit	0 unit
Total Energy Requirements	15560 MWh	9425.8 MWh	7100 MWh	4970 MWh
Microgrid CAPEX	39.4 M$	31 M$	17 M$	12.8 M$
Cons	Energy independence, ship autonomy	Zero emission, good energetic efficiency	CAPEX	CAPEX
Pros	CAPEX, energetic efficiency.	Ship autonomy management, CAPEX.	Dependence on fossil fuels, greenhouse gas emissions.	High greenhouse gas emissions, dependence on fossil fuels.

promises the environmental benefits compared to previous renewable energy scenarios. This compromise between initial cost and environmental impact underlines the dilemma inherent in finding a sustainable and economically viable energy solution.

6 Conclusions

This study explores sustainable energy solutions for Ushant, aiming for total autonomy by exploring different scenarios integrating renewable energies and maritime mobility. The simulation tool, developed in Matlab Simulink, evaluates the efficiency, energy requirements and quantity of fuel consumption. The first scenario offers significant autonomy with a costly infrastructure, while the second presents challenges in managing vessel autonomy. The balance between economic viability and environmental sustainability guides the choice of scenarios for a well-informed energy transition. In future work, the focus will be on optimizing the energy management strategy, and on integrating the boat-to-grid concept. This concept is based on the idea of using the energy/power system of ships when they are docked in the island harbour, thus opening up new prospects for more flexible and sustainable energy management.

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