Université de Lorraine

Master Erasmus Mundus in

Decentralised Smart Energy Systems

Case Base Module:

Hydrogen energy storage for a renewable energy community: technical and behavioural design of a self-sufficient system

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Table of Contents

Table of Tables:

Table of figures:

1. Introduction

Energy sector is responsible for 73.2% of global greenhouse gas emissions [1], making energy transition the best starting point for climate change mitigation. One of the solutions is renewable energy communities, which were proposed in directive 2018/2001 by European Parliament [2]. These communities involve groups of citizens, who contribute to energy transition by producing, distributing and investing in renewable energy. The benefits of joining such a community include self-sufficiency, reduction in greenhouse gas emissions, economic development, energy security and unity of the involved citizens [2].

This project is focusing on a group of 11 households, driven by the idea of contributing to climate change mitigation and self-sufficiency. This renewable energy community is willing to construct and later live in a collective residential building located in Metz, France, producing energy with the help of solar photovoltaic panels and storing it with Lithium-Ion batteries and hydrogen storage system. The technology behind this energy system has to be as environmentally friendly and autonomous as possible. The renewable energy community members are willing to decrease their consumption to achieve their goals. Therefore, the behavioural analysis is performed along with technical and economical ones.

The technical feasibility of such a system will be investigated by first defining and calculating the associated energy demand, then choosing commercially available equipment to compose the system and their quantities, sizing and area of occupation. The storage possibilities – lithium-ion batteries and high pressure hydrogen gas storage – will be considered and investigated. The technical design will be then evaluated on the basis of the system's efficiency and the economic feasibility.

To address the economic feasibility of the project a cost analysis is carried out, taking into account all the different kinds of expenses that come with the energy system. It is outlined that the resulting cost of energy finally consumed by the members of the community is higher compared to the average cost of electricity in France. A loan solution is also proposed in order for all the community members to be able to tackle with the high initial costs of the energy system.

The user plays a central role in an energy system, having almost the same influence on energy consumption as the technology behind it [3]. The energy system must be designed in a way that will be usable and easily understandable by the inhabitants, otherwise the adverse effect is possible [4]. The needs of the users, factors that influence their decisions and possible interventions are therefore to be analysed and implemented into the design of self-sufficient renewable energy system.

2. Technical Design

In the following section it will be estimated the size of a photovoltaic (PV) solar system integrated with Hydrogen seasonal storage and a Lithium-ion batteries storage to compensate the difference in production and demand during day and night. More on this choice will be explained on section 2.4.1. All the calculations will be based on the assumption that the system has to be self-sustainable, meaning that there should be no use of power from the national electricity grid. The values presented here are estimations to determine the feasibility of the system, and, in case of implementation it is necessary to review the project with personal data and make an optimization for the system design.

2.1. Case description

With the global warming raising more and more concern over the years, the European Union has been putting into place measures to promote the use of renewable energies, including the authorization to create "renewable energy communities". With that in mind, a group of 11 households, composed of 18 adults and 3 children, are joining together to start their own off-grid community.

The building will be located in Rue des Violettes, 57000 Metz, on latitude 49.08065666207945 and longitude 6.184370953590991. The terrain surface area is 1878 m^2 and the maximum building surface they can build is 563 m^2, which can have two floors. The lot have an estimated price of 550 000 €. The lot shape and size are presented in APPENDIX 1 – The lot.

In Metz, the summers are partly cloudy, and the winters are very cold, windy, and mostly cloudy. Over the course of the year, the temperature typically varies from *-1°C* to *25°C* and is rarely below *-7°C* or above *32°C*. The clearest month of the year in Metz is July, during which on average the sky is clear, mostly clear, or partly cloudy 61% of the time and the cloudiest month of the year is December, during which on average the sky is overcast or mostly cloudy 75% of the time. Finally, the shortest day of the year is December 21, with around 8 hours of daylight and the longest day is June 21, with around 16 hours of daylight. [5]

The fact that the sky is covered with clouds for most of winter is not ideal for a photovoltaic system. That shows in the irradiance received for the area, presented in Figure 1, which was made using data obtained from RETScreen Clean Energy Management Software for a typical meteorological year (TMY), based on ground and NASA data for France - Metz/Frescaty (FAFB) (the closest weather control station to the terrain location). The original data obtained from the software is presented in APPENDIX 2 – Weather data from RETscreen. However, the location temperature ranges are perfect for a PV application, considering that the efficiency and performance ratios decrease with an increase in temperature.

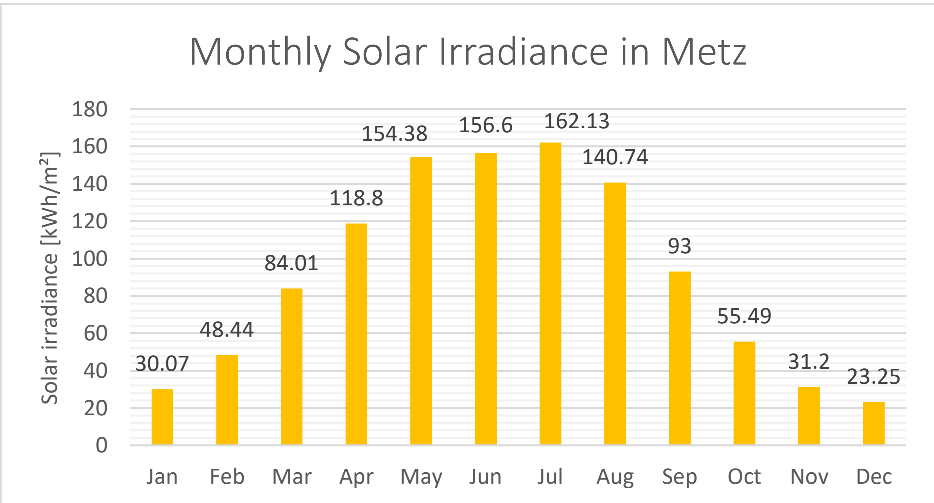

Figure 1: Monthly solar irradiance

2.2. Energy Demand profiles

Since this work is based on a hypothetical case, there is no previous information on the families' energy consumption. Because of that, this section will estimate the energy demand of the household based on many energy use assumptions and average values for France. In this building, the energy needs are for electricity, hot water, cooking and ambient heating. It will be considered that all of those will be achieved using solely electric appliances.

The first thing to determine is the size of each apartment. We have 4 single people, 4 couples and 3 families of 3. The energy consumption is very directly related to the house sizing, so it is necessary, as the people want to be energy conscient, to reduce the area of living. However, since this is a lifetime investment, it is important to give them a reasonable level of comfort. Having that in mind and considering that the apartments will be composed of a combination of a smaller bedroom of 12 m^2 and/or a master bedroom of 18 m^2, kitchen of 10 m^2, living room of 15-20 m^2, laundry room of 3 m^2 and bathroom of 5 m^2, it was reached an approximate area of 40 m^2 for a single person's apartment, 60 m^2 for the couple's and 80 m^2 for the family of 3. With that there is 640 m^2 of apartments. Considering about 100 m^2 of common shared areas and that it will be distributed over 2 floors, the final building area will be of around 370 m^2.

It was then calculated an estimation on how much time they would spend at home, based on their activities. That was made considering that people that work full time would be out of the house for around 10 hours a day, 5 days a week, people on telecommuting would be away 10 h only on the days that they are not telecommuting, the kids that go to school would spend around 6 hours away from home, 5 days a week, and everybody is home all the time during the weekend. The time at home for the household was then defined based on the family member who spends more time at home. A daily average was calculated dividing the weekly time by 7 days. The results are presented in the following table.

Table 1: Description of households

	Age	Place of work	Hours at home [h/week]	Hours at home [h/day]	Area [m^2]
	55	Workplace	118	16.9	40
	35	Full telecommuting	168	24.0	40
	29	Workplace	118	16.9	40
	27	Workplace	118	16.9	40
Couple 1 - Member 1	38	Workplace	118	16.9	60
Couple 1 - Member 2	39	Workplace			
Couple 2 - Member 1	43	2days/week telecommuting	138	19.7	60
Couple 2 - Member 2	47	Workplace			
Couple 3 - Member 1	51	Workplace	118	16.9	60
Couple 3 - Member 2	54	Workplace			
Couple 4 - Member 1	32	2days/week telecommuting	138	19.7	60
Couple 4 - Member 2	30	2days/week telecommuting			
Family 1 - Member 1	2	-	138	19.7	80
Family 1 - Member 2	25	2days/week telecommuting			
Family 1 - Member 3	27	2days/week telecommuting			
Family 2 - Member 1	3	School	168	24.0	80
Family 2 - Member 2	29	Full telecommuting			
Family 2 - Member 3	33	2days/week telecommuting			
Family 3 - Member 1	11	School	138	19.7	80
Family 3 - Member 2	39	Workplace			
Family 3 - Member 3	41	Workplace			
				Total:	640

Using “Selectra Energy Calculator for France”, it is estimated that a typical French household with all electrical appliances would consume yearly, for the previously defined apartment sizes and one, two or three family members, respectively 4634 kWh, 6471 kWh and 8309 kWh. [6] From the Odyssee database on Sectoral Profile – Households it is estimated that about 65% of the energy consumption in European households go towards ambient heating, 14% to water heating, 19% on electrical appliances and cooking and the remaining 2% goes for lighting and others. [7]

To estimate the minimum energy consumption possible to the system, the main sources of consumption were calculated separately, reducing each of them as much as possible while still considering a reasonable level of comfort for the inhabitants. The energy demands considered here are ambient heat, water heat and general electricity. Considering the location and weather, it was not considered any need for cooling.

The main consumption is in heat, which was calculated for each separated apartment using the method of degrees-day of heat [8], according to the following equation, and assuming that the heating will be done by electric heat pump with coefficient of performance (COP) of 3. [9]

$$EH_{month} = \frac{UA\, DD_{heat}\, t_{day}}{COP_{HP}}$$

The total electric energy consumed monthly for heating each of the apartments, EH was calculated considering that the building will have very good insulation, with an average heat loss coefficient of U = 0.93 W/ºC/m^2 [10]. The heat loss area A was calculated for each size of apartment, considering an average of heat loss through 2 lateral walls and the ceiling and a ceiling height of 3m. The degrees-day of heat, DD_{heat}, necessary for each month were obtained from the software RETscreen, from the weather station nearest to the building site and are presented in APPENDIX 2 – Weather data from RETscreen. This parameter is considering that the indoor temperature of the apartments will be set to 18ºC, which is still a comfortable indoor temperature but minimizes the energy use. The number of hours per day, t_{day}, that the heating system is on is the time that the inhabitants are at home, as presented in Table 1. In this case, is considered, for energy saving purposes, that the inhabitants will turn off the HVAC system off when they are not at home. The detailed results for each apartment are presented in APPENDIX 3 – Demand of Energy for Ambient Heating.

To define the electricity consumption (for home appliances, lighting and cooking), first a simulation was made in Selectra Energy Calculator for France [6] considering the following criteria:

- There is no need for heating or hot water, since we are calculating those separately.
- The cooking is done by electrical induction plate.
- Electrical appliances included are one oven, one television, washing machine, dishwasher, fridge, and other normal electro domestic equipment.
- There will be no drying machine, to reduce energy consumption.
- The initial value obtained is for people who are all day at home. It was then made a simple extrapolation considering the number of hours at home for each household.

The average electricity consumption obtained for the single, couple and family apartments were, respectively, 1476 kWh/year, 1772 kWh/year and 2069 kWh/year. Based on experience and considering that this electricity is only for the lights and home appliances, not including heating and hot water, these values are a little higher than expected, so a reduction of 10% will be made to it to get a more realistic average demand. Besides that, considering the need of minimizing the system, for environmental and financial aspects, a goal of a further 30% reduction in this consumption is expected to be achieved with the implementation of technics to change user behaviour, therefore the final expected electricity demand is reduced. More about that is described in section 4 – Behavioural . Finally, considering that a big part of this share is destined to consumptions that do not have a very significant seasonal change, it was assumed that the electricity consumption would be approximately the same every month. With this, it was obtained that the building monthly electricity consumption should be around 762 kWh.

For the electricity consumed to heat hot water, it was considered that the water will be heated by an energy saving electric heater. Hot water use varies a lot between different households, but accordingly with experimental data, we can consider an average of 4 kWh per day (based on 2.4 occupants; approx. 80 litres of hot water at 55°C). [11] Here the user's behaviour technics will help to keep this consumption up to around 1.5 kWh/person/day. In this case again it will be considered that there is not a very significant seasonal change in the energy demand, so the final monthly consumption for the building is 958.1 kWh.

The more detailed calculation on electricity and water energy need is presented on APPENDIX 4 – Electricity and hot water demand. By summing the three main energy needs described above, we obtain the following total energy demand for the building:

Table 2: Building's yearly energy need

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
5065	4602	4139	3441	2494	1803	1720	1720	2342	3261	4208	4913	39708

Now, since we have an intermittent energy source which only provides energy during the day, it will be necessary to plan a storage system to compensate the nightly energy demand. For that, it is necessary to have an idea on the variation of consumption during the day. Using the daily load curve of electricity consumption in France [12], shown in Figure 2, and considering sunrise and sunset hours for winter, since it's the period when there will be the bigger need for the storage system, it was made a simple integration to obtain the percentage of the total energy that is consumed during the night period. From this was concluded that about 66% of the total daily energy demand needs to be stored during the day to compensate for the night period.

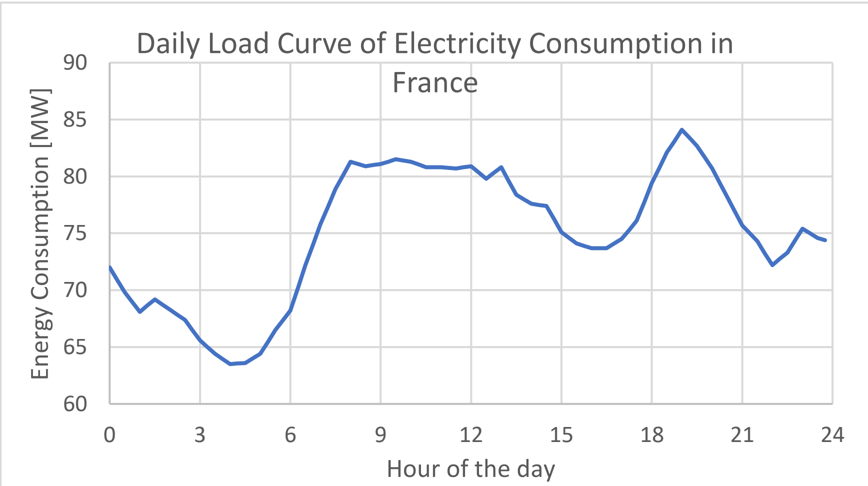

Figure 2: Daily load profile

2.3. Solar PV System Sizing

2.3.1. Choice of Solar Panel

The solar system will be calculated having as a parameter the PV panel model Sharp NU-AF370. This choice was made considering that this panel is made of monocrystalline silicon, has a high nominal power of 370 W for a very reasonable price of 114€/module, high module efficiency of 19.0%, is tested and certified in the European Union, has 10 years of product guarantee and 25 years of linear power output guarantee, and finally, it is easily available for purchase and has a local support team in Europe. [13]

This panel has a surface area of 1.96 m x 0.992 m = 1.944 m^2. In standard test conditions (STC), it has an open circuit voltage of 48.82 V, short circuit current of 9.87 A, maximum power point (MPP) voltage of 39.66V and MPP current of 9.33 A. The detailed specification sheet is presented in APPENDIX 5.1 – Solar PV panel.

2.3.2. Quantity of solar panels

To determine the ideal size of the solar PV plant, we started calculating a minimal number of solar panels to meet the average yearly demand of energy. This was done by the yearly average since the demand in winter is much bigger than the summer demand, but the winter production is much smaller. In order not to oversize the PV plant to be able to meet the winter demand, we are planning the system to meet the yearly average using Li-ion batteries to compensate day/night energy shift and the H_2 system to compensate for the seasonal storage, since it is not economically feasible to do the seasonal storage using only batteries (see Section 2.4.1).

However, because the hydrogen storage has a roundtrip efficiency of only around 30% [14], as described in Table 4, we need to add extra panels to compensate for the energy loss in the conversion. By adding extra panels, we will also be producing more energy every month, so the problem was solved by doing a numerical optimization where the total energy surplus produced from the solar system, multiplied by the storage efficiency, results in nearly the same amount of energy demanded from H_2 to compensate the under sizing of the system for winter months. This optimization considering the monthly data is presented in Table 5.

The peak power necessary from our PV system is given by the following equation:

$$P_p = \frac{Y_f}{h_p\, PR}$$

Where P_p is the peak PV power installed and Y_f is the final energy yield of the system, which has to meet the demand calculated in section 2.2. The number of hours of solar in peak, h_p , represents how many hours it would take, if we had the sun always in STC with a level of irradiance of G = 1000 W/m^2, to reach the total amount of irradiance for the determined period of time (here considered one month). The global monthly irradiance measured for our location is presented in Figure 1 and the resulting the h_p for each month is shown in Table 5. The number of solar peak hours per year is obtained by the sum of the monthly ones.

$$h_{p,month} = \frac{Global\ monthly\ irradiance\ [kWh/m^2]}{Standard\ peak\ irradiance\ [kW/m^2]}$$

The PR is the performance ratio of the system, which represents all imaginable energy losses in the system, such as real power of the PV modules below nominal rating, mismatch, wiring, shades, dust, overheating, conversion DC/AC, failures, etc. In a PV panel, the efficiency drops with the increase in temperature. Because of that, thermal losses are very dependent on the climate and the PR of a PV system fluctuates from one place to another, and along the course of a year or a day. For example, the PR of a given PV system located in the North of France is higher than the PR of the same system installed in the South of the country, because the weather is colder in the north. It was obtained by research data the average PR for residential PV in France, per month, shown in Table 5, and for the calculation of the minimal number of panels the yearly average was used. [15]

Finally, after having the peak power calculated, the number of panels for the system is given by the ratio between the peak power of the total system by the nominal power of the solar panel we chose to use, which in this case is 370 W, as described in section 2.3.1.

$$N = \frac{P_{p,system}}{P_{N,panel}}$$

Table 3: PV panels calculation

Nominal Power	370	W
Average year PR	0.76	
Energy Need/year	39708	kWh
Solar peak hours/year	1098.11	h
Peak Power needed	47.5789	kW
Minimal n. of PV panels	129	panels
Extra PV Panels	85.0	panels
TOTAL PV panels	214	panels

Table 4: Hydrogen Storage Efficiencies

	Efficiency
Fuel cell	0.47
Electrolyser	0.7
Compressor	0.89
TOTAL	0.293

Table 5: Optimization of solar PV

	Days	Solar Peak hours [h]	PR	Solar Energy Production from PV [MWh]	Energy Demand [MWh]	Energy Surplus [MWh]	Energy to/from H_2 system [MWh]
Jan	31	30.07	0.78	1.857	5.065	-3.208	-3.208
Feb	28	48.44	0.8	3.068	4.602	-1.533	-1.533
Mar	31	84.01	0.79	5.255	4.139	1.116	0.327
Apr	30	118.8	0.78	7.337	3.441	3.896	1.141
May	31	154.38	0.75	9.168	2.494	6.674	1.954
Jun	30	156.6	0.74	9.176	1.803	7.373	2.159
Jul	31	162.13	0.74	9.500	1.720	7.779	2.278
Aug	31	140.74	0.73	8.135	1.720	6.415	1.878
Sep	30	93	0.75	5.523	2.342	3.181	0.931
Oct	31	55.49	0.76	3.339	3.261	0.078	0.023
Nov	30	31.2	0.755	1.865	4.208	-2.343	-2.343
Dec	31	23.25	0.745	1.371	4.913	-3.541	-3.541
TOTAL		1098.11	0.76	65.595	39.71	25.89	0.07

Finally, we can have an overview of our system's production and user's demand, where the problem of the mismatch in the consumption and production profiles becomes very clear.

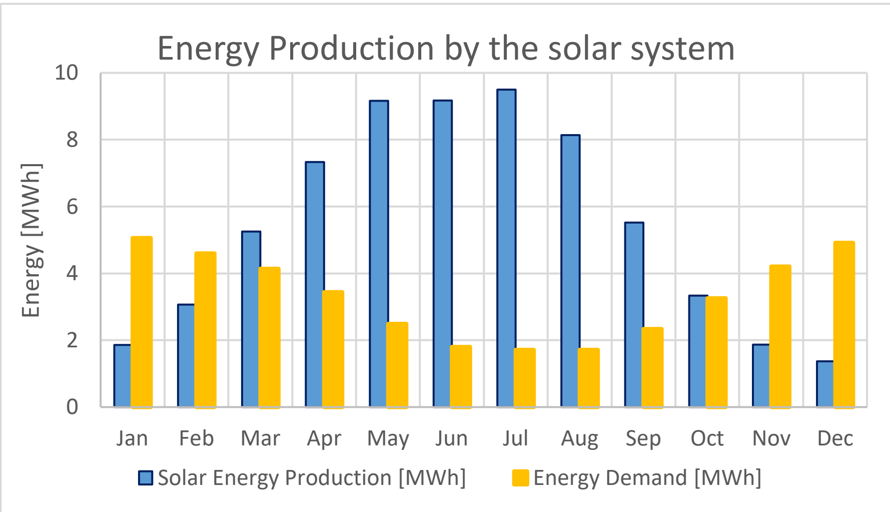

Figure 3: PV plant yield vs energy consumption

2.3.3. Area occupied by the system

When positioning the solar panels on the terrain, it is important that they face south, to maximize the energy collected. Since we are at a high latitude, the panels must be inclined, like shown in Figure 4. The optimum tilt angle can vary from 72º in December to 27º in June, according to the seasons and position of the sun in the horizon. Since we need maximum production for the months of bigger demand (winter), we should optimize the angle for that season. Based on the solar movement over the year, it is possible to calculate, through trigonometry, that the ideal angle for spring and autumn equinox would be the same as the latitude, of around 49º, and for the winter solstice it would be around 72º (latitude + 23º of the solar declination) [16]. To have the best results during the lower period of production, an angle between those two is the best option. Here it will be used 10º more than the equinox, to improve winter production without compromising the efficiency for the whole year. So β = 49º + 10º = 59º. [17]

Now, to calculate the minimal distance d between the panels and the area occupied by them, we need to consider the size of the shade created by the row of panels directly in front. The day with biggest shade in the year, in the northern hemisphere, is 21st of December. For that reason, we will calculate the size of the shade, d, for midday of the winter solstice, and add a little increment to decrease the loss of power due to shading. The solar angle can be obtained by online solar calculator [18]. A scheme of the shading area is given in Figure 4.

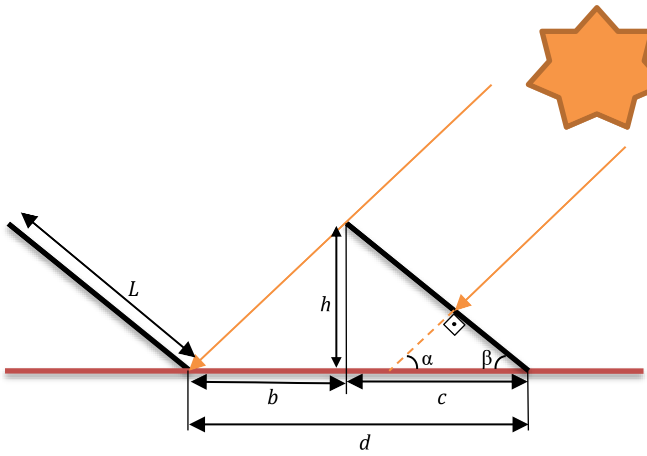

Figure 4: Solar panels inclination and shade area

Considering this, we can calculate the height h of the system by:

$$h = L \sin \beta$$

Where L is the length of the panel chosen, and β is the panel tilt angle. Then with the solar angle α we can calculate b_{min} and the final value of b should be slightly bigger than the minimum b, $b \geq b_{min}$.

$$b_{min} = \frac{h}{\tan \alpha}$$

Finally, d is given by:

$$d = b + c = b + L \cos \beta$$

An approximation of the total area occupied by the PV system can now be calculated using the width of the chosen panels, W, and the total number of panels.

$$A_{PV} = N_{panels} \cdot A_{panel} = N_{panels} \cdot d \cdot W$$

The results of previously mentioned calculations are given in Table 6.

Table 6: Solar shading and terrain occupation

Latitude	49.0807	º
Solar angle at 21/12 at noon (α)	17.24	º
Tilt angle (β)	59	º
Length of each module (L)	1.96	m
Width of each module (W)	0.99	m
Height of system (h)	1.68	m
Min (b) for shading winter solstice	5.41	m
Chosen distance (b)	5.50	m
Distance for each line (d)	6.51	m
Total area occupied with panels (A_{PV})	1381.9	m²
Terrain	1878	m²
Solar on top of building	370	m²
Solar for the terrain	1011.9	m²
Left over terrain area	496.1	m²

To be possible to install the PV system, due to the very high area of occupancy obtained, it will be necessary to have part of it on the rooftop of the building and the remaining panels on the ground. Because of the shape and orientation of the terrain, while possible to install the system, it will leave very little outside area for the installation of storage system and the personal use of the residents (such as parking, garden, playground, clothesline, etc). This can be seen more clearly in Figure 5. Due to that, would be recommended for the inhabitants to check into other options of terrains for the installation.

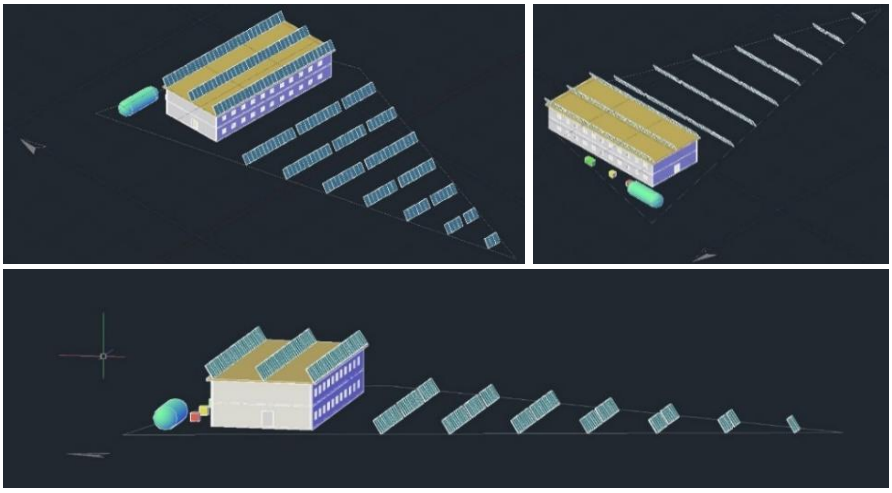

Figure 5: Allocation of components in the terrain

2.4. Sizing of the Storage System

2.4.1. Introduction to the choice of storage system

The aim of the system designed is to be energetically self-sufficient, with all of its energy being generated by PV panels. Because of the daily and seasonal intermittence of the solar energy source, supplying the energy demand without using storage or another source of energy (such as diesel generator or connection to the main power grid) is not feasible. Therefore, energy storage is essential for the functionality of the proposed system. There are many different ways to solve this problem. In this project it will not be considered any other source of energy besides the one generated by the PV and only Lithium-ion batteries or hydrogen as storage options.

If the system used only batteries for storage, it would be an advantage on the point that they are very easy to manage. However, considering the huge amounts of energy necessary, the very low capacity of the battery banks, and the high price of batteries, this solution would be too expensive and space consuming. Technically, other problems would rise, such as the need of a cooling system to control the temperature of batteries, some safety measures would need to be put in place in case of fire, among others. Furthermore, batteries have a very limited life span, meaning the entire system needs to be replaced after some years of service. The production of Li-ion batteries is very energy consuming, have high cost of materials, the mining of Lithium is extremely polluting to the environment and imply in social issues to the miners [19] [20]. In addition, after its lifetime is over, due to technical constraints, economic barriers, logistic issues, and regulatory gaps, most of the batteries end up without a proper recycling, generating waste and making necessary more extraction of the raw materials. [21]

On the other hand, hydrogen is also considered a feasible way to store energy. It can be used by the implementation of an electrolyser to split water and produce H_2 from the excess of electricity generated by the PV during the warmer months of the year, in association with a fuel cell, which will convert this hydrogen back into electricity to supply the higher winter energy demand. The main advantages of this system are that it has the possibility of long-term storage with no auto discharge, and it also has a very low environmental impact. [22] However, the roundtrip efficiency of this system is very low, close to 30% only, which means that to generate the same amount of electric energy, if going through the storage system, it is necessary more than triple the number of solar panels, which implies in higher cost of equipment, higher area of terrain, a much bigger financial investment and much more complex maintenance. Besides that, the electrolyser is more complex to operate and control, compared to the batteries, and the H_2 gas is highly inflammable and has to be stored in very high pressure, rising many economic and safety concerns to mind. [14]

In this proposition, is not possible to use only the batteries for seasonal storage, considering the economical constraint of the future inhabitants of the building. The option of using the batteries only to supply a few days of autonomy and oversize the PV system to be able to supply the entire winter demand is also not feasible: firstly due to weather conditions in the region, which would make necessary too many days of autonomy, and therefore, too many battery banks; and secondly, because the number of PV panels installed (and consequently the area occupied by them), is limited by the relatively small area of terrain available. Nevertheless, it is also not possible to use only H_2, because, considering that more than 65% of the daily energy is consumed during the night (number explained in section 2.2, page 5), its low efficiency would again raise too much the number of needed solar panels. Finally, the best option for this system is hybrid energy storage, where the batteries will be recharged during the solar hours and discharged during the night, and the hydrogen system will only store the energy needed to compensate for the seasonal difference in production and demand, where H_2 will be produced during warmer months and consumed to cover the excess in the demand during winter.

2.4.2. Sizing of system

2.4.2.1. Hydrogen electrolyser and storage tank

As presented in Table 5: Optimization of solar PV, the PV system can produce more energy than consumed from March to October. This extra amount of energy has to be converted into H_2 and stored for the moments of energy shortage. This is done by the use of an electrolyser.

The power of the electrolyser was estimated considering the peak power of the PV system, which is 47.6 kW, as calculated in Table 3. The electrolysis is done by water splitting, having the following global reaction:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

And the molar flow rate of hydrogen going through the electrolyser at its peak production can be calculated by the maximum power generated divided by the free Gibbs energy of the reaction, ΔG_{water} is -228.2 kJ/mol, as shown in the following equation.

$$n_{H_2,elect} = \frac{P_{max}}{-\Delta G_{water}} \quad [mol/s]$$

The model of electrolyser chosen is described in APPENDIX 5.2 – Electrolyser H2B2 EL10N and its most important characteristics are presented in Table 7. [23]

Table 7: Description of the electrolyser

Electrolyser	H2B2 EL10N	
Power	53.2	kW
Number of stacks	1	
Voltage	230	V
H_2 Flow rate ($n_{H_2,elect}$)	0.2085	mol/s

From the electric energy surplus generated by the PV from March to October, given in Table 5, we can calculate, using the electrolyser and compressor's efficiencies (shown previously on Table 4, $\eta_{electolyzer}$ = 0.7 and $\eta_{compressor}$ = 0.89), the total amount of energy generated monthly in the form of fuel [14]:

$$E_{H_2} = E_{ele} \times \eta_{electolyzer} \times \eta_{compressor} \;\; [kWh]$$

The amount of hydrogen stored, in mol, is given by the molar flow rate of hydrogen multiplied by the production time, which can be obtained from the energy stored divided by the power:

$$N_{H_2} = \frac{E_{H_2}}{P_{max}} \times n_{H_2,elect} \;\; [mol]$$

Now, the total mass of hydrogen stored in the system can be obtained by using H_2 molecular weight, which is approximately 2 g/mol:

$$m_{H_2} = N_{H_2} \times M_{H_2} \quad [kg]$$

Finally, this H_2 will be stored in a high-pressure tank, with the storage conditions being of 200 bar as working pressure and 291.15 K (from factory data). At these conditions, the H_2 will not behave exactly as an ideal gas, but we can get a rough approximation of the total volume of storage by using the perfect gas law:

$$V_{Hydrogen} = \frac{N_{H_2}\, R\, T}{P} \;\; [m^3]$$

The results for previously mentioned calculations are shown in Table 8, as well as a monthly status of the H_2 tank, which is given by the sum of the previous month status with the volume generated or consumed in each month.

Table 8: Status of Hydrogen storage

Month	Electric energy to H_2 system [MWh]	H_2 Energy [MWh]	H_2 added to tank [mol/month]	H_2 added to tank [m^3]	Status of H_2 Tank [m^3]
					0
Mar	0.327	0.695	10971	1.328	1.328
Apr	1.141	2.427	38294	4.635	5.963
May	1.954	4.158	65590	7.938	13.901
Jun	2.159	4.593	72459	8.770	22.671
Jul	2.278	4.847	76458	9.254	31.925
Aug	1.878	3.996	63045	7.630	39.555
Sep	0.931	1.982	31260	3.783	43.338
Oct	0.023	0.049	767	0.093	43.431
TOTAL	10.69	22.75	358 844	43.43	

As highlighted in Table 8: Status of Hydrogen storage, the size of tank for hydrogen storage should be of approximately 45 m^3. The hydrogen tank chosen is shown in APPENDIX 5.3 – Storage tank, and have an estimated price of € 50 959, obtained by the calculator in the website “Match Equip-Cost” [24].

In order to achieve the required storage pressure in the tank, it is necessary to add a gas compressor to the system. The component chosen is the “High-pressure breathing diving air compressor 200bar 220v TRD-H-W”, described in APPENDIX 5.4 – Compressor, with a market price of € 1547.80 [25].

2.4.2.2. Fuel cell

During winter, from November to February, the energy produced by the PV is not enough to cover the user’s energy consumption. Therefore, the stored hydrogen is converted back to electricity via the use of the fuel cell. From the selecta website we can know that the base power offered for a French household is of 6 kVA [6]. Considering that we have 11 households, the power necessary from the fuel cell was estimated as 11 x 6 kW = 66 kW. The Fuel Cell model chosen is the EKPO – PEMFC, stack module NM5-EVO (detailed information in

APPENDIX 5.5 – Fuel cell). [26] It has a voltage V of a single cell of 0.6 V, electrolyser area (A) of 190 cm^2 and its current density (i) is 2 A/cm^2. The power of a single cell is given by:

$$P_{single\ cell} = V_{single\ cell} \times i \times \ A \qquad [W]$$

The number of cells needed, which is 290, is calculated by dividing the required power by the single cell power:

$$N°_{cell} = \frac{P_{user}}{P_{single\ cell}}$$

Now, the global reaction of the fuel cell is the opposite of the electrolysis:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

And to get the molar flow rate for the fuel cell, we can apply the same method used for the electrolyser:

$$n_{H_2,FC} = \frac{P_{user}}{\Delta G_{water}} \qquad [mol/s]$$

The entire description of fuel cell is given in Table 9: Information of fuel cell.

Table 9: Information of fuel cell

Fuel Cell model	EKPO - PEMFC	
Number of cells per stack	290	
Single cell voltage	0.6	V
Single cell power	228	W
Total Voltage	174	V
Total power	66120	W
Current density	2	A/cm^2
Area	190	cm^2
Total current	380	A
H2 Flow rate fuel cell	0.28975	mol/s

Now, the energy needed to be generated by the H_2 system is the shortage of electrical energy to complete the demand, as presented in Table 5: Optimization of solar PV. Considering that the efficiency of the fuel cell is only 47%, we can calculate by the following equation the amount of energy in the form of fuel that needs to be removed from the storage and converted. [14]

$$E_{H_2} = \frac{E_{ele}}{\eta_{fuel\ cell}} \qquad [kWh]$$

The amount of hydrogen consumed, in mol, is given using the molar flow rate in the fuel cell, in the same manner as before.

$$N_{H_2} = \frac{E_{H_2}}{P_{fuel\ cell}} \times n_{H_2,FC} \qquad [mol]$$

The volume removed from the tank and the tank status are also calculated as for the electrolyser. The final results are showed in Table 10: State of hydrogen for consuming.

Table 10: State of hydrogen for consuming

Month	Electric Energy from H_2 system [MWh]	H_2 Energy [MWh]	H_2 removed from tank [mol]	H_2 removed from tank [m^3]	Status of H_2 Tank [m^3]
Jan	3.208	6.825	107661	13.030	6.498
Feb	1.533	3.262	51466	6.229	0.269
Oct					43.431
Nov	2.343	4.984	78632	9.517	33.914
Dec	3.541	7.534	118859	14.386	19.529
TOTAL	10.62	22.61	356 619	43.16	

2.4.2.3. Li-ion Battery Storage

The battery chosen for this project is the BYD Battery-Box Premium LVS 24.0, for its reasonable price per kWh of stored energy, its ease of purchase for European applications and its possibility of integration between different modules. This battery module costs €10 059, has a voltage of 51.2 V and a capacity of 24 kWh, or 469 Ah. Detailed description is given in [27].

To calculate the number of batteries required for the system, it is necessary to decide on the depth of discharge (DOD) of the batteries. In research, M.I. Hlal et al., found that the ideal de DOD of their system was

70%. [28] The depth of discharge of Li-ion batteries can be used even up to 100%, but that has a significant effect on the battery's life expectancy. [29] For this case, with a depth of discharge of 70% it would be necessary to use 6.63 modules, while for 80% would be necessary 5.8 modules. The depth of discharge was then optimized to 78%, for the use of exactly 6 modules.

The energy to be stored was calculated based on the daily demand profile, detailed in section 2.2.

$$Energy\ to\ be\ Stored\ = \frac{Daily\ load\ [Wh]\ x\ fraction\ of\ energy\ for\ the\ night}{Depth\ of\ discharge\ of\ battery}\quad [Wh]$$

The minimum capacity required for the batteries is then given by:

$$Min\ system\ capacity\ required\ = \frac{Energy\ stored\ [Wh]}{Voltage\ of\ system\ [V]}\quad [Ah]$$

And finally, the number of batteries is given by:

$$N_{batteries} = \frac{System\ storage\ capacity\ [Ah]}{Single\ battery\ capacity\ [Ah]}$$

The results are presented in the following table.

Table 11: Battery modules

Depth of discharge	0.78	
Entire day energy demand	168.82	kWh
Fraction of energy used at night	0.66	
Night energy demand	111.42	kWh
Energy to be stored for one night	142.85	kWh
Min system's stored capacity	2790.03	Ah
Min Number of battery modules	5.95	banks
Actual Number of battery modules	6	banks
Total stored capacity	2812.50	Ah

2.5. Characterization of the energy system

When we look at the whole system, it should be composed by the PV panels, a charger controller, the storage system, an inverter and if possible, a backup system to keep the essentials running in case of failure of the microgrid. The scheme is shown in Figure 6: Energy system composition.

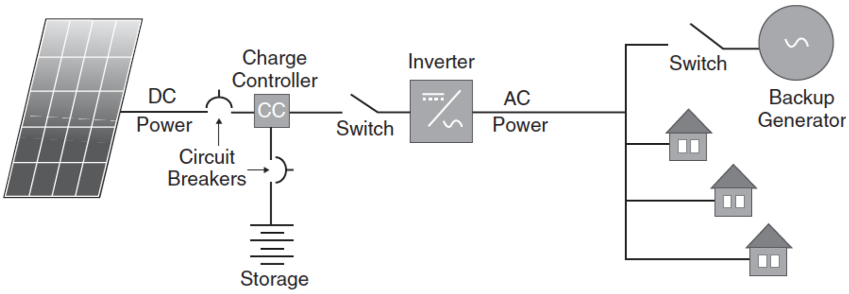

Figure 6: Energy system composition

The PV panels and storage systems are already defined at this point. The panels will be connected in 17 parallel lines of 12 modules in series, plus one line with 10 modules in series. For the inverter, it was chosen the "GoodWe GW50KN-MT Solar Inverter", which has 4 MPPT trackers and have the intervals of maximum and minimum voltage currents which supports the values obtained from our solar system, presented in Table 12: Configuration of PV system. The description of the inverter's characteristics is presented in APPENDIX 5.7 – Inverter. [30]

Table 12: Configuration of PV system

Modules in Series	12	
Lines of modules in Parallel	17.83	(17 line x 12 modules + 1 line x 10 modules)
Max power Voltage	39.66	V
Open Circuit Voltage	48.82	V
Max power Current	9.33	A
Short Circuit Current	9.87	A
System's max power Voltage	475.92	V
System's Open Circuit Voltage	585.84	V
System's max power Current	166.39	A
System's Short Circuit Current	176.02	A

For this case is not being considered any backup system, considering its high cost and the intention of the inhabitants not to resort to non-renewable energy sources. The intention will be that the inhabitants maintain control of their demand to avoid excess consumption and a consequent blackout.

2.6. Global System Efficiency

The system's global efficiency can be calculated by the fraction between the final amount of energy obtained/consumed and the total irradiance received in the PV surface of the entire system. This gives the system a global efficiency of 8.7%, according to Table 13.

$$\eta_{system} = \frac{Energy\ Consumed}{N_{panels}\ A_{panel}\ Irradiance}$$

Table 13: System Global Efficiency

Total PV panels	214	
Area of one PV panel	1.944	m²
Total Area of PV	416.1	m²
Yearly irradiance	1098	kWh/m²
Total irradiance received	456907	kWh
Total Energy Consumed	39708	kWh
System Global Efficiency	8.69	%

We can also estimate the overall efficiency based on the energy consumed over the total energy produced by the solar system. With that, we get the following:

$$\eta = \frac{E.Consumed}{E.Produced} = \frac{39.71\ MWh}{65.595\ MWh} = 0.6053 \approx 60.5\%$$

3. Financial and Economic Analysis

This section is dedicated to the financial and economic analysis solely of the energy system. All the expenses for the construction of the building are not looked into.

3.1. Hardware costs

Hereby the hardware prices and quantity of the components chosen for the system are resumed.

Table 14:Hardware costs

	Unit price (€)	Quantity	Total Cost (€)
PV Panels	114,00	214	24396,00
Electrolyzer	900,00	48	43200,00
Fuel cell	900,00	66	59400,00
Compressor	1547,80	1	1547,80
Hydrogen tank	50959,00	1	50959,00
Li-ion Batteries	10059,00	6	60354,00
Inverter	2840,00	1	2840,00
Charge Controller	111,00	1	111,00
		Total	**242 807,80**

The price for the charge controller has been taken from [31]. The price for the fuel cell and the electrolyser has been taken from [32]. The prices of the other components have already been discussed in the previous sections or can be found in the APPENDIXES.

3.2. Subsidies

The French government provides a premium for auto-consumption when installing photovoltaic systems [33]. Unfortunately, in our case, seeing that the system is not connected to the grid, it doesn't satisfy the conditions to take advantage of this subsidy, as when the PV panels produce energy in surplus, this is not injected into the grid but, if possible, stored in one of the storage systems.

3.3. LCOE

In order to address the economic feasibility of the project a cost analysis is carried out, taking into account the different installation, operation and maintenance costs of all the components of the system, when this data is available. In order to evaluate the cost of energy production the concept of Levelized Cost of Energy (LCOE) needs to be introduced. The LCOE is an economic assessment of the cost of the energy-generating system including all costs over its lifetime: initial investment, operations and maintenance and cost of capital. There are two methods for estimating the LCOE: the first one considers a yearly timeframe, so it returns a yearly estimate of the LCOE. The second one, instead, keeps the whole lifetime of the facility when computing its LCOE; it thus results in a life-cycle estimate. In the present analysis the latter is the one used, as it provides a higher degree of accuracy by assessing the whole life cycle of the facility.

In the following equation the LCOE is displayed as the sum of the initial investment I_0 and the costs of the facility during its lifecycle, divided by the total energy production over its lifetime, which is considered to be of 25 years:

$$LCOE = \frac{I_0 + lifecycle\ costs}{lifetime\ energy\ production}$$

The stream of real future costs and energy outputs identified in year t are discounted back with a discount rate r, to a present value. The discount rate provides a measure of the potential viability of the project. The rate chosen for this evaluation is $r = 5{,}96\%$, as calculated in [34].

The present value of costs C_t is then divided by the present value of lifetime energy output E_t. The stream of real future costs and energy outputs identified are discounted with the discount rate r for an investment period of 25 years:

$$LCOE = \frac{\sum_{t=0}^{25} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{25} \frac{E_t}{(1+r)^t}}$$

The present value of costs is equal to the sum of the initial investment I_0 and the total operation and maintenance costs M_t (result of the sum of the operation and maintenance and substitution costs of each component of the system). The final equation used to evaluate the Levelized Cost of Energy is

$$LCOE = \frac{I_0 + \sum_{t=1}^{25} \frac{M_t}{(1+r)^t}}{\sum_{t=0}^{25} \frac{E_t}{(1+r)^t}}$$

The initial investment I_0 is not discounted as it is a one-off payment made the starting year. It can be furtherly divided into the sum of installation costs I and hardware costs H. The data availability on the different components of the system is diverse. If the available data is presented in USD the exchange rate of 1.137 USD/€ will be used, as provided by Europe Central Bank [35].

The hardware costs for PV panels are the one presented in Section 3.1. The installation costs for PV include, mechanical installation (construction), electrical installation, inspection, system design, permitting and customer acquisition. The sum of the previous installation costs is of $426{,}97 \frac{€}{kW}$ of installed power [36]. The values refer to 2019. Costs for racking and cabling is also taken into account. As presented in [36], the price for each is, in order, $86{,}38 \frac{€}{kW}$ and $41{,}6 \frac{€}{kW}$ of installed power.

The operation and maintenance (O&M) costs for fixed axis PV panels, which are the ones chosen, is to be considered as of 1% of the total initial cost of the PV system [34]. They comprise system monitoring, emergency response, corrective maintenance and system repairs, scheduled preventative maintenance, array/panel cleaning and weed and vegetation control. O&M costs for cabling and frames are comprised in the PV panels costs.

The hardware cost for the inverter is presented in Section 3.1. The O&M costs for the inverter only consist of the inverter substitution, which is made every 10 years.

The cost of the batteries is given in Section 3.1. Installation costs for lithium-ion storage includes site design costs, costs related to equipment procurement/transportation, and the costs of labour/parts for installation. It amounts to $89 \frac{€}{kWh}$ [37]. Operation and maintenance costs for the lithium batteries is, in percentage, similar to the O&M costs for the PV system, and is considered to be of $10 \frac{€}{kW}$ installed [38].

O&M costs for the electrolyser is considered to be 1,5% of the initial cost [39]. The same value is taken for evaluating the costs for the fuel cell. Maintenance for the compressor and the hydrogen storage tank is low, so O&M for these components is supposed to be zero. Because of lack of available data, seen that installations of hydrogen storage system are still not spread, the installation costs of the hydrogen storage system are not taken into account.

All the aforementioned costs are shown in Table 15 for the system sized in Section 2.

Table 15:Costs

	Hardware (€)	Installation (€)	Initial Costs (€)	O&M (€/year)
PV Panels	24396,00	33807,66	58203,66	582,04
Inverter	2840,00		2840,00	
Cabling	3294,22		3294,22	
Charge Controller	111,00		111,00	
Lithium-ion battery	60354,00	12819,74	73173,74	768,00
Electrolyzer	43200,00		43200,00	648,00
Compressor	1547,80		1547,80	
Hydrogen Tank	50959,00		50959,00	
Fuel Cell	59400,00		59400,00	891,00
Total (€)	**246102,02**	**46627,41**	**292729,43**	**2889,04**

The resulting LCOE comes to be of 0.44 $\frac{€}{kWh}$. The average electricity price in France is 0.19 $\frac{€}{kWh}$ [40]. This means that, in financial terms, for the community would be better to be connected to the grid. However the main desire and interest of the community is not to make profit, but to be able to build a system which reliably and environmentally friendly ensures energy autonomy.

It is interesting to see how, no matter the reductions in energy consumption of the households discussed in Section 2.2, the LCOE of this type of off-grid community is still high, also taking into account that installation costs of the hydrogen system were not taken into account. This hints us to think that, in order for this type of solution to become more affordable, the market needs time, particularly for technologies such as hydrogen storage for housing to become more commercially mature and ready.

3.4. Loan

In order to have an idea of the impact of the first-year costs (the initial costs) on the monthly budgets of the inhabitants of the community, a loan analysis has been carried out. It is supposed that the members of the community don't have any savings. The net income of each working inhabitant is supposed to be equal to the average French net income, 2340 $\frac{€}{month}$ as of 2022 [41]. The initial costs are divided between the inhabitants proportionally to the square meters of their household compared to the total ones. The loan chosen for this study is an amortized loan, which is a fixed interest loan with fixed monthly payments. The fixed interest rate of the loan (i) is 2.15% [42], for a loan duration (N) of 300 months (25 years), the entire lifetime of the system. For each household, the due monthly payment is calculated as such

$$monthly\ payment = initial\ cost \cdot \left(\frac{1-(1+i)}{1-(1+i)^N} + i \right)$$

as shown in [43]. In Table 16 the monthly loan payment is shown for every type of household (single, couple, family), together with the repartition of the initial costs and the total income of the household.

Table 16: Loan

	Initial cost repartition [€]	Monthly income [€]	Monthly payment [€]
Single	18295,59	2340,00	78,89
Couple	27443,38	4680,00	118,33
Family	36591,18	4680,00	157,78

4. Behavioural Analysis

In order for the system to be successfully used by users, behavioural analysis is performed. It includes User's needs analysis and solution to these needs, behavioural design and evaluation.

4.1. Users' Needs analysis

User's needs analysis is a crucial part of the user-centred design. It provides useful information about the user, their needs and therefore helps to define the utility and the characteristics of the artefact, so that it can be successfully used by users and bring them satisfaction [44].

4.1.1. Analysis of the Personas

The personas represent the types of users that will use the designed system. Inhabitants are divided into personas, the full description of which can be found in APPENDIX 6 – Personas – The Involved and The Passive. Given two different types of users - the Involved and the Passive - the respective analysis was conducted in order to provide the best solution for both. The analysis is divided into 3 main sections to better understand and compare both personas: Energy System Installation, Energy System Management and Energy Consumption Management.

4.1.1.1. Energy System Installation

The Involved persona wants to contribute to the installation of the system as much as possible, building the house and the energy system together with other inhabitants. Persona acknowledges that without professional help the system cannot be insured and worries about the compatibility of the technologies. The Passive persona, on the contrary, wants the work to be done by professionals or to the very least supervised by them. At the same time, they also want to be able to choose the type of energy and the technology for the system.

4.1.1.2. Energy System Management

The Involved persona wants to be able to manage the energy production system and be able to carry out basic repair and maintenance works for the system. Their main concern lies in the excess of production and the choice of usage of the energy - the persona wants to be able to choose what to do with produced energy and be able to share the excess. The Passive persona does not want to be involved in the energy system management. They are afraid of the frequent breaks of the system and of the lack of knowledge in order to participate in making important decisions about the system.

4.1.1.3. Energy Consumption Management

The Involved persona is willing to adapt to the amount of energy available and the weather anticipation and expects other inhabitants to do the same. They want to know the amount of energy left and spent, however are not aware of how to convert the units to understandable amounts, e.g. hours of cooking in the oven. The Passive persona only agrees to reduce the energy consumption if it does not reduce her comfort. They want to live without too many constraints and directions from their neighbours and find it difficult to understand what consumes the most and how to reduce it. Additionally, the persona finds traditional energy management devices guilt-based and intrusive, therefore discouraging.

4.1.2. Needs' description

User's needs related to energy for housing include several categories. The general needs come from the goals of the personas relative to the system they want to install for their housing. These goals include:

- Using energy sources with respect to the environment
- Involvement in control of the energy system
- Independence from energy suppliers and state
- Security of the system
- Self-sufficiency
- Comfort
- Collective and shared values among neighbours
- Profitability

Personas value these goals differently, however respect towards the environment, self-sufficiency and independence are highly valued by both. The usage of renewable energy technologies, such as solar panels used in the design, is corresponding to the environmental goals.

User's needs also include different types of activities undertaken by users. They are divided into four categories: domestic activities, energy system installation, energy system management and energy consumption management.

4.1.2.1. Domestic activities

Domestic activities are divided into four main categories: space heating, water heating, cooking and electricity for lighting and appliances. The division and the weight in total consumption based on the research "Household energy consumption by end-use in the EU-27" conducted by the European Environmental Agency [3]. The resulting graph is given in Figure, where the percentage from the total consumption is calculated relatively to the total amount of energy consumed.

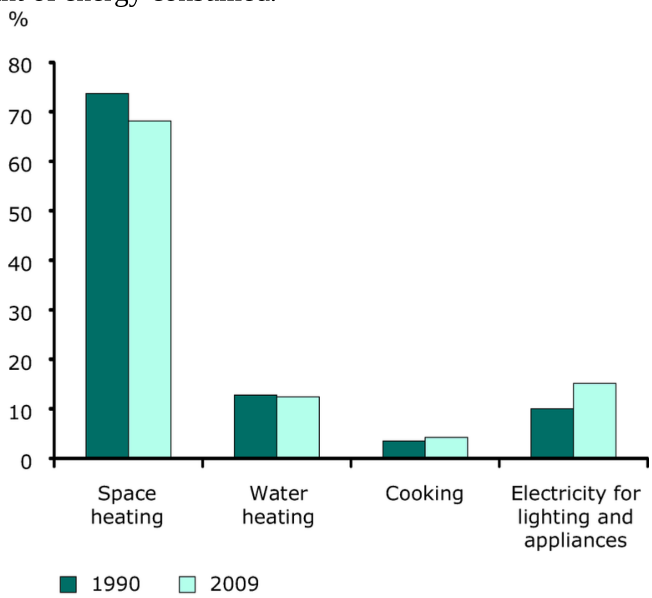

Figure 7:Share of energy consumption by end uses in total households consumption in percent [45]

The domestic needs are therefore summarised in these 4 categories in Table 17, with the description of the appliances used, weight in total consumption and possible design-related constraints, in the table below. The design constraints section indicates the possible constraint faced when trying to apply energy usage reduction methods.

Table 17: The user's domestic activities needs by category of end use, appliances associated, weight in total consumption and design constraints

Users' Energy Domestic Activities Needs			
Category of End Uses	**Appliances**	**Weight in Total Consumption**	**Design Constraints**
Space heating	Heater	68%	The working hours of a heater is hard to reduce, since low temperature significantly reduces comfort of the user. Heater is usually working all the time during the winter season.
Water heating	Boiler	12%	Water consumption tends to be high, reducing the amount of hot water usage is hardly possible due to cold showers being an unpopular option
Cooking	Oven, fridge, stove, microwave, small cooking appliances such as kettle, slow cooker, blender, coffee machine etc	5%	The fridge must work all of the time, otherwise the food will be spoiled.
Electricity for lighting and appliances	Lights, TV, computer/laptop, laundry, cleaning appliances (e.g. dishwasher, vacuum cleaner etc), air conditioning	15%	Users tend to leave the light switched on, however if all the lights are motion-sensor, they can switch off randomly, creating big inconveniences for users

4.1.2.2. Energy system installation/renovation

The Involved persona wants to be involved in the system installation, therefore there are energy system installation and renovation needs. Both personas are willing to be able to choose the technology. These needs include such activities as:

- decision on the technology
- design of the system
- anticipating the exploitation
- work planning
- administration
- financing
- installation and renovation
- compliance check

4.1.2.3. Energy system management

Both personas expressed their desire to be able to choose the way produced energy is used, therefore there are energy system management needs. The Involved persona additionally wants to be able to repair and maintain the system in condition on a basic level. The energy system management needs are formed of:

- check-ups
- keeping in condition
- repair
- supply energy
- choose the use of energy
- distribute

4.1.2.4. Energy consumption management

Both personas expressed their opinions and concerns regarding the energy consumption management. Both are willing to be able to see how much they spent and how much is left, as well as they are ready to reduce their energy consumption without heavily reducing their comfort. The energy consumption management needs include:

- consult consumption
- anticipate/simulate consumption
- understand consumption
- consult the available energy
- anticipate/simulate available energy
- change activity
- act on equipment

4.1.3. User's needs survey

To analyse the needs of users to a greater extent, the survey is used as an additional method. The survey is intended to discover more about the users' habits, the use of appliances, which energy-reducing means they are willing to adapt and which type of the consumption management they would prefer. The user has to rank the use of certain appliances, express an opinion about certain proposed measures and give feedback in the end. The results of this survey are therefore used for the additional analysis of their needs and behaviour and implemented in the design of the energy monitoring system.

The user's needs survey (Survey 1) can be found in the APPENDIX 7 – Surveys. It is not administered, only designed as proposition.

4.2. Solutions to the needs

After the needs and the survey results have been analysed, the solutions to the needs are presented. The solutions include the proposed ways to make the energy system desirable and successfully usable, as well as the decrease in energy consumption smooth and with the least decrease in user's comfort. The solutions are provided in the Table below:

Table 18: User's needs divided into 4 categories, associated proposed solutions and needs met

Activity	Solution	Needs met
Domestic activities	Common laundry	Electricity for lighting and appliances
	Better insulation	Space heating
	Energy-efficient appliances	Electricity for lighting and appliances, Cooking, Water heating
	Motion-sensor lights together with energy-efficient lights, so that in case of no-movement activities the light still can be switched on	Electricity for lighting and appliances
Energy System Installation	Involve professionals in the construction process as supervisors	Installation and renovation, compliance check, design of the system
	Provide information about the compatibility of the technology and the advice on the best combination	Anticipating the exploitation, design of the system, decision on the technology, compliance check
	Provide advice on financial solution	Financing, administration, work planning

Energy System Management	Issue a user manual to provide users with the information about basic repairs and maintenance processes of the energy system	Check-ups, keeping in condition, repair
	Allow users to see where the energy is going (used/stored)	Supply energy, choose the use of energy, distribute
Energy Consumption Management	Install the special display in each household for users to track their energy consumption, which includes the amount of energy left and the interactive mode where the energy reduction scenarios could be seen and therefore adapted	Consult consumption, anticipate/simulate consumption, consult the available energy, change activity, anticipate/simulate available energy
	For easier understanding, the energy in the display will also be converted to hours of using particular device	Understand consumption
	The display will be showing the weather forecast and approximate energy production for the next day	Anticipate/simulate available energy, consult the available energy
	The display will show the amount of energy generated by solar panels, the amount stored and the amount used	Act on equipment, consult consumption

4.3. Behavioural Design

In this section, we intend to understand the willingness of the users to adopt new housing energy saving measures and, subsequently, influence their behaviours through suitable interventions.

4.3.1. Factors that influence users' decisions

Prior to proposing measures that could decrease a household's energy consumption, it is important to identify the factors that play a role in altering the inhabitants' behaviours toward energy. S. Ebrahimigharehbaghi et al [46] describe four types of factors: contextual factors (e.g., building characteristics and household profiles, policy incentives), personal factors (e.g., awareness of energy consumption, attitudes, and perceptions of households of electricity/gas consumption, cognitive biases, experience skills), motivational factors (e.g., increased comfort (thermal comfort), cost savings on energy bills, paybacks, carbon footprints) and barriers such as access to information.

4.3.2. Interventions to influence users' behaviours

The most successful results in efforts to reduce households' energy consumption were seen when individuals were not only aware of the problem and actions they could take, but when they were equipped with the skills to act effectively and successfully [47]. Therefore, to achieve the best outcome possible in this specific housing project, we focus on two types of interventions: structural and informational.

4.3.2.1. Structural interventions

The structural interventions aim to modify the conditions in which the households make decisions regarding their energy consumption.

First, we intend to create community programs that would translate into peer-to-peer energy education and support. The energy ambassadors involved in these programs live in the same neighbourhoods as the residents and actively contribute to making their neighbourhoods more sustainable by initiating programs or helping their neighbours renovate the buildings more efficiently in terms of energy. Peer-to-peer education is effective because peers are more vulnerable and less anxious with someone they relate to as compared to figures of authority and perceived superiority, ultimately increasing confidence and the ability to learn [47].

Concretely, the ambassadors will contact residents interested in participating, help to install smart equipment (e.g., smart thermostats) in homes, communicate and forge relationships with participants, as well as educate and collaborate with them to achieve energy savings [47].

Secondly, we will systematically encourage access to energy-efficient technologies by pre-installing them into the houses and persuading the homeowners to perform energy-efficient renovations when conducting general maintenance, be it through financial incentives (using specific billing methods) even though these types of incentives might not be sustainable in the long run.

4.3.2.2. Informational interventions

Through the informational interventions, we plan to induce reflection by providing feedback to the users after the behaviour has been carried out and provoke forward thinking (energy planning) by giving them early choices through a specifically designed energy planner tool (4.3.2.3 Energy+).

Access to information on all the possibilities for an energy-efficient and sustainable house, the transparency on the electricity billing methods, the steps to becoming natural gas-free, and finding a professional or company that can help take the best decisions will definitely influence the users' knowledge and motivation, which are direct determinants of behaviour. In addition, S. Ebrahimigharehbaghi et al [46] show that the inclusion of social norms in information provision (such as neighbours joining in community programs as described in the structural interventions) enhances the effectiveness of the information provision.

By utilizing feedback and forward thinking to make energy consumption tangible and connecting to emotions and societal values, we will be able to leverage social and emotional nudges to promote energy conscious behaviours. The goal being pursued with this second type of intervention is to have the users understand that they can take control of their energy consumption (and therefore their bills) by learning about the relationship between behaviours, consumption, and bills [47]. An interactive energy planner tool called "Energy+" has been specifically designed and implemented with Python and its GUI package tkinter to use information as a nudge to alter users' behaviour.

4.3.2.3. Energy+

Energy+ aims to keep the users informed in real-time about the current state of their energy system. It will be installed in each household, connected to the sensors of the overall electrical system to gather relevant information about the energy production and consumption, as well as to the Wi-Fi to provide weather forecasts and related notifications. Each household will possess a unique account and will access the app whether on computers or mobile devices.

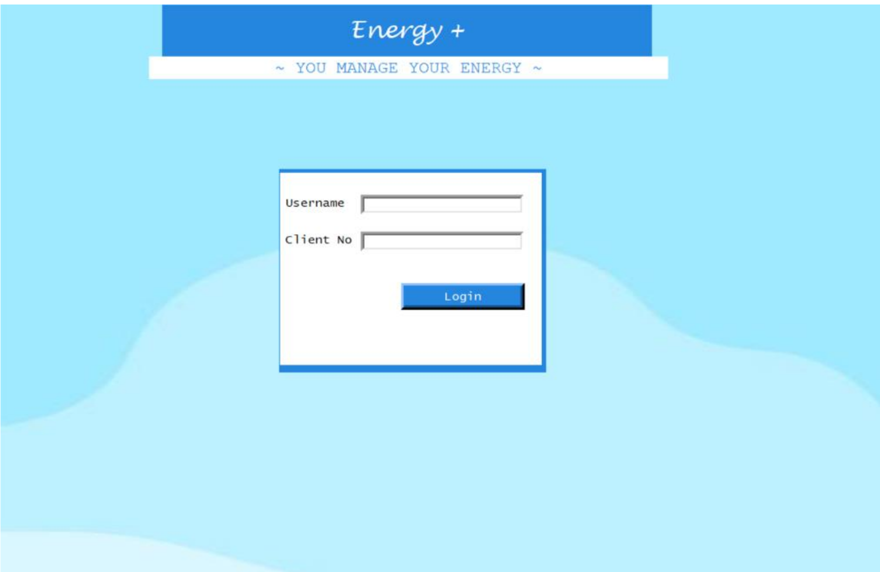

Figure 8: Login Page of Energy+ for the users to access their account

Energy+ consists of three main features implemented using distinct interfaces: weather and forecasts, energy consumption and energy planner.

A. Weather and forecasts

On this interface, the users will have access in real time to the amount of energy generated, used and stored during the day.

Furthermore, they are provided with a weather forecast feature which enables them to input the name of their city of residence and see the forecast for the next four days. This forecast feature also comes with a set of notifications that serve as alerts helping the users to become aware of possible fluctuations in their amount of energy generated and stored. Finally, by clicking on the Energy-saving suggestions button, the users will head directly to the energy planner interface in which they will find automatic recommendations suggested by Energy+ (Recommendation Scenarios) to optimally reduce consumption based on the weather fluctuations (Figure 8).

B. Energy Consumption

The Energy Consumption interface shows a statistical overview of the users' energy consumption. They will be able to choose a month of the year and review the daily energy consumption for that month as well as the distribution of the consumption in four categories of end-uses: space heating, water heating, cooking and electrical appliances. This feature is intended to increase the awareness of the users regarding their own consumption as they will concretely observe its evolution and distribution over the months. Additionally, it serves as an invitation to forward thinking (energy planning) which is implemented on the third interface (Figure 9).

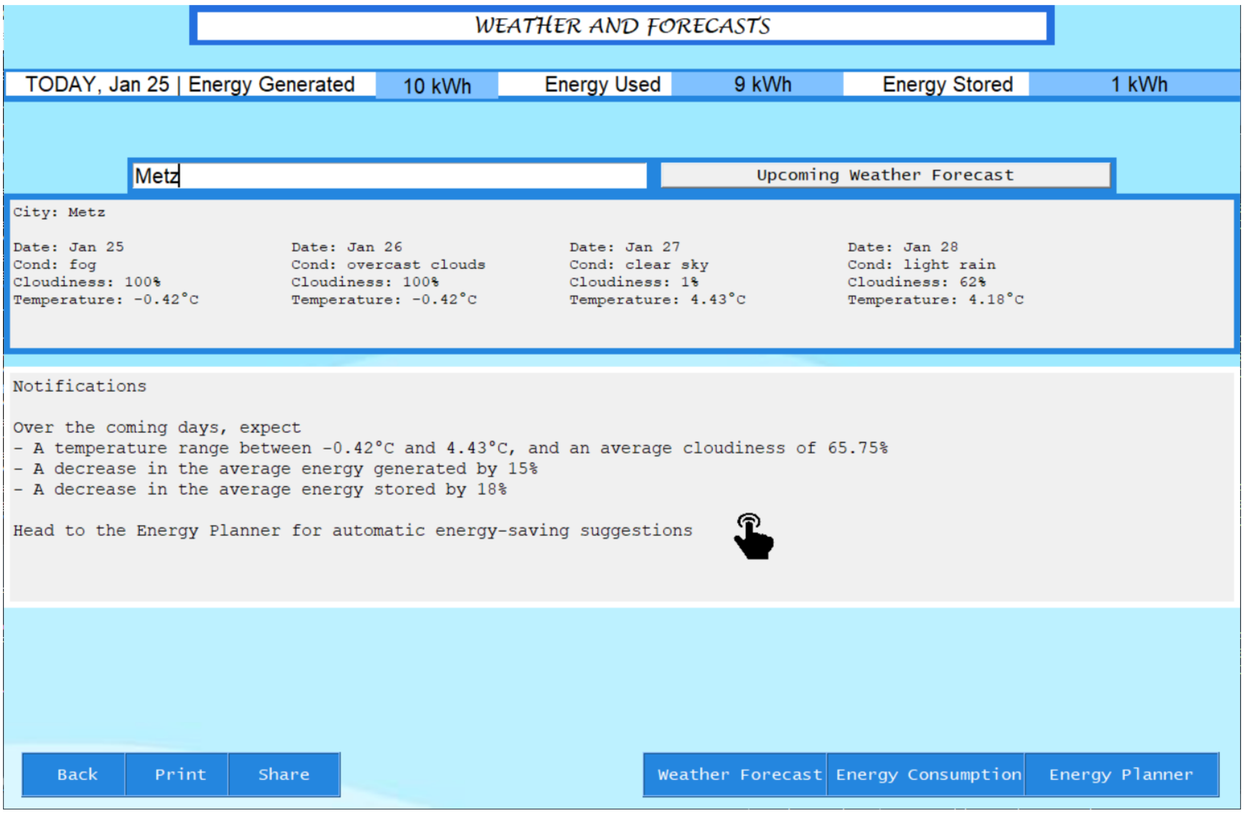

Figure 9: Weather Forecast Page intended to provide information and notifications to the users

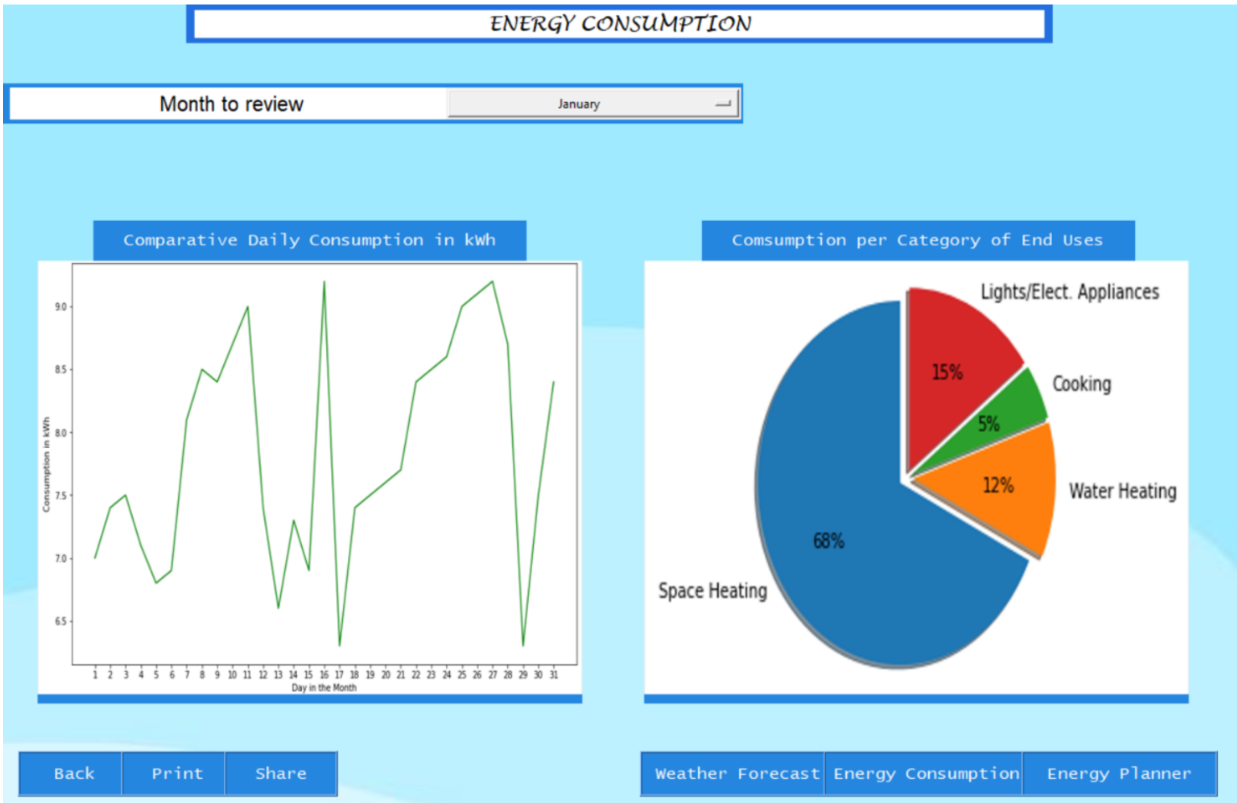

Figure 10: Energy Consumption Page with data to increase awareness of an household's current consumption

C. Energy Planner

The interactive energy planner is designed to help the users stay within the range of energy availability for the month. Month is chosen as the unit of time in this case because it seems easier and more practical to assess the users' detailed behavioural pattern and the most efficient interventions needed in that timeframe.

By toggling the sliders, the users can adjust (increase or decrease) their consumption in percentage (which is subsequently translated into concrete daily actions, for e.g., decreasing the heater slider to –50% corresponds to a decrease of 60 minutes per day in the usage of the heater). The sliders are grouped into the four categories previously mentioned: space heating, water heating, cooking, lights and electrical appliances. Each category contains subcategories that are consistent with the users' typical needs in a household. The users can, therefore, displace multiple sliders simultaneously, either increasing, decreasing, or keeping the slider value at 0 i.e., business as usual.

As the users adjust the sliders, the energy planner tracks the amount of energy used by each appliance and when the button RUN is pressed to simulate the outcome of the chosen energy reduction scenario, Energy+ will show in percentage whether the suggested measures taken by the users will be within the available energy for the month i.e. ≤ 100% or beyond the average energy available i.e. > 100%. The users can try different scenarios indefinitely or consult the recommended scenarios under the "Recommended Scenarios" button.

When the users move the slider to the left, it indicates a reduction in the usage of a given appliance, and movement to the right means the opposite, an increase in usage. Furthermore, a comment in text format will appear below the slider, indicating how many hours or minutes of usage that the change corresponds to.

The Energy Planner intends to effectively give the users the means to plan, decide and control their consumption. When they want to be actively involved, they can set their own standards and verify whether it lies within their energy budget. Conversely, they might as well rely on the automatic recommendations provided by Energy+.

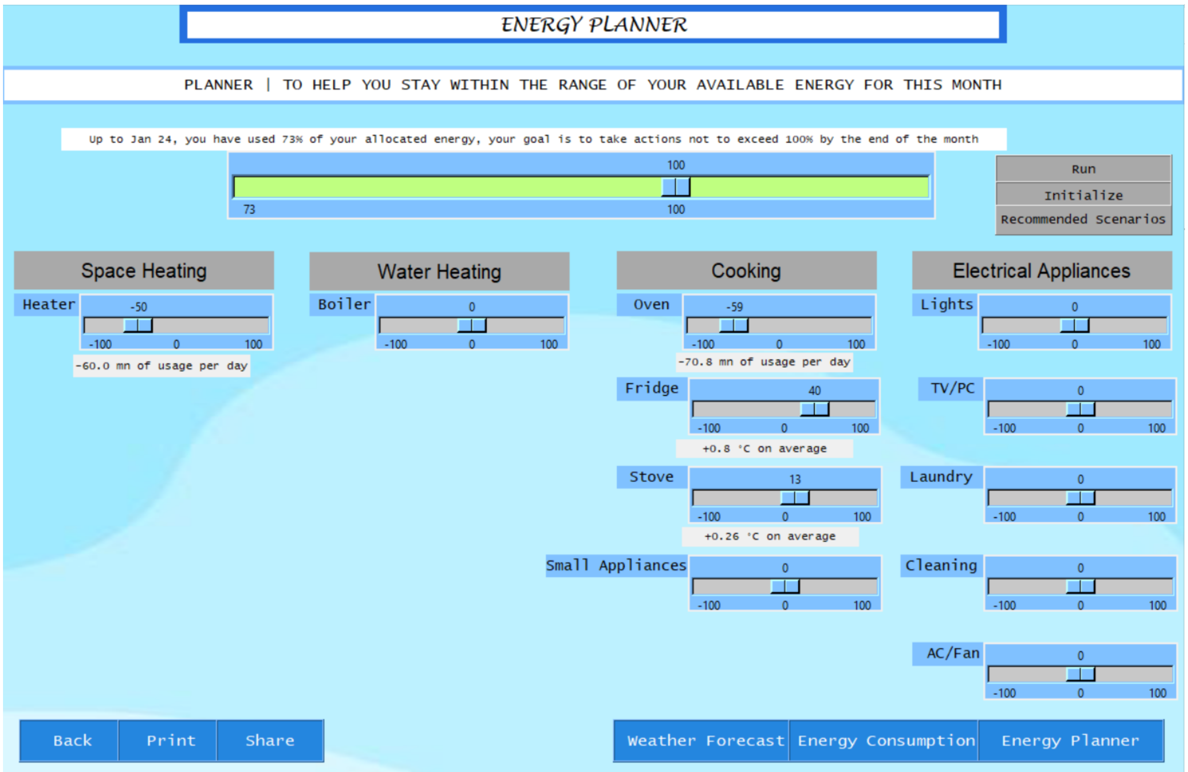

Figure 11: Energy Planner Page giving simulation options and optimal scenario features to the users

To access Energy+ and give a try, one can follow (https://drive.google.com/drive/folders/1sxLqLCbTjyp3UCODEuq52sNNw7w6t19N?usp=sharing) to download the file named *'dist'*, open it and run the executable file labelled *'Energy+.exe'*. Then, the app should be automatically triggered.
A demonstration video can also be found here (https://www.youtube.com/watch?v=hNCByKByH54).

4.3.2.4. Interventions applied to each category

Subsequently, the abovementioned interventions (structural and informational) will be applied on each of the four categories of end uses previously defined. Table 19 indicates the behavioural interventions associated with each category and the expected reduction in energy consumption as a result. The reduction in consumption is estimated based on the high efficiency on the new electrical appliances available on the market and the expected positive response from the users following the described behavioural interventions.

Table 19: Behavioural interventions applied to each category of end-uses with expected reduction in energy consumption

Category of End Uses	Energy-saving measures	Behavioural Interventions	Expected Reduction in Energy Consumption in %
Space heating	Sustainable heating systems (smart thermostat / more energy-efficient boilers/ insulated roofs, walls and floors/ double-glazed windows)	Peer-to-peer education Pre-installation Renovation/ Sensibilization	10
Water heating	Smart thermostat Water-efficient appliances	Feedback Energy Planning	5
Cooking	Energy-efficient appliances (stove, fridge, rice pressure cooker)	Peer-to-peer education Feedback Energy Planning (cooking in advance, UberEATS)	5

Electricity for lighting and appliances	Management of the usage of electronic devices (use timers/smart power strip, unplug computer, TVs, microwaves, light bulbs, lamps, dishwashers) Laundry (hang clothes to dry air/ use cold water when possible) Air conditioning (use ceiling or floor fans instead/ use of timers)	Feedback Energy Planning Peer-to-peer education	10

The table below provides an overall summary of the main problems encountered by the users in housing energy systems, the interventions and their related application mechanisms proposed in this project as well as the expected outcomes in terms of reduction of energy consumption and user satisfaction.

Table 20: Summary of the problems identified, interventions suggested and expected behavioural outputs

Problems	Behavioural Interventions	Mechanism	Behavioural Output
Information on Energy Reduction Mechanisms	Community Programs (Sensibilization) Feedback / Energy Planning	Peer-to-peer education and support Energy+	Reduction in Energy consumption
Practical representation of the energy values and units. Interpretation of weather data	Access to information	Energy+	Understandable data Forecasts Decision Planning
Renovation/Maintenance of the energy system	Community Programs	Peer-to-peer support	More environmentally friendly choice during repairs / maintenance /
Installation of equipment	Documentation Support	User Manual Peer-to-peer support	Participation in the installation with professional supervision
Insurance (in case of equipment failure or problems during installation)	Access to professionals or company in this industry	Professional advice	Confidence in the installation and equipment as insurance will be covered by the company in charge
Control over the management of the energy system	Documentation Support Convenient management interface	User Manual Peer-to-peer education Energy+	Planning, System Control / know how to repair
Worries regarding reduction of comfort	Energy planning tool	Energy+	System managed by users themselves Reduction in consumption with self-imposed reduction in comfort

4.4. Evaluation and limits of the solutions

4.4.1. Evaluation

1. Survey:

In order to evaluate the suitability and usability of the overall system proposed in this project, we design an evaluation survey (Survey 2 in APPENDIX 7 – Surveys) that is structured around these main concepts: system's usability, users' satisfaction, and assessment of effective reduction in energy consumption. The survey includes various types of questions such as rankings, agree or disagree, multiple choice, and openended response. Each question is analysed to evaluate the question format to utilize, the proper language to use, and where to include the question within the survey. Ideally, we will submit the evaluation survey to the users after one full year of living in the houses such that we can collect more complete and relevant feedback on the performance of the system throughout all 4 seasons.

2. Data Analytics:

To measure energy consumption changes as a result of alteration of behaviour, we will also access the monthly energy consumption data of the residents. All users will be first asked to sign release forms guaranteeing confidentiality and permitting researchers to access their monthly energy consumption data. Researchers can then use these data in addition to monthly residential billings to create insights and provide long term recommendations. [47]

4.4.2. Potential Improvements

In the long run, it could be beneficial to directly hire and train community members to complete energy efficiency upgrades and installations on top of the energy ambassadors to achieve even more significant results. Furthermore, we could utilize smart Wi-Fi thermostat data, building energy and geometrical characteristics data, occupancy data, and energy and water consumption data to generate machine learning models predicting the monthly energy consumption. These models would provide continuous data needed to analyse energy efficiency and identify areas for improvement, along with estimates of the financial value of the investments [47].

5. Conclusion and perspectives

After the technical analysis, a system is obtained which is mainly composed of 214 PV panels, 6 battery banks of 24 kW capacity, one PEM electrolyser and PEM fuel cell and 45 m^3 of hydrogen storage. The obtained system efficiency is 60.5% and the global efficiency (when considering the total energy received in the PV surface) is 8.7%. These values are very good, considering the low roundtrip efficiency of the H_2 storage and the solar PV efficiency of 19%.

The PV and the building will occupy around 1400 m^2 of the 1878 m^2 of terrain, with the remaining for the installation for the storage system and inhabitants' use. However, considering the shape and orientation of the terrain, it is difficult to make an adequate distribution of the PV system, considering that it's necessary for them to be allocated south of the building to avoid shading. Because of that, there is a very small leftover area for the use of inhabitants. A bigger free outside area would be more advantageous for the community, so it would be better if a slightly bigger terrain with a bigger side facing south was purchased.

For the energy and storage system, because of the low efficiency of hydrogen system, the number of PV panels have to be almost doubled to compensate the energy demand. While the results are feasible, the high percentage of area of terrain occupied and having a 45 m^3 tank of hydrogen in the backyard is not ideal. The lack of a backup system is also a problem, considering that if for any reason one of the equipment stops working, there is no way of stopping a blackout. One option that could be interesting would be to have a hybrid PV system, having the national grid as a backup in case of problems or overconsumption. With a hybrid system like that it would also be possible to decrease the system size, since there would be the possibility of covering some of the peak energy demand using electricity from the grid.

The results of the economical analysis show that the Levelized Cost of Electricity linked to the described system is more than two times greater than the average price of electricity in France. The costs of the equipment necessary to build the system are still high, in particular costs of the hydrogen storage system: they account for more than 50% of the total initial costs and for almost 70% of the energy storage initial costs. We would expect the prices of such technologies to decrease as they become more mature and spread into the utility scale energy use environment. In Table 16 the monthly payment to cover the initial costs is for every household, if the community manages to obtain an amortized fixed rate loan over a period of 25 years. The monthly payment would amount to about 3% of the monthly income of the working members of the community.

The analysis of the needs of users was performed through analysis of their personas and needs and creating a survey, resulting in proposed solutions with the aim of making the system usable and decrease in consumption performed without big losses in comfort. These solutions include motion-sensor lights, common laundry, energy-effective electronics, help from professionals, user manual and better insulation. The analysis of factors that can influence user's decisions led to creation of suitable interventions along with the solutions of user's needs. The interventions include peer-to-peer education and support, renovation and energy planning, that is mainly executed through the display with the Energy+ program. Energy+ behaves as the main tool to help users to know how the energy is spent and how they can reach their monthly goal in decreasing their consumption with suitable measures, to follow the weather forecast to predict the amount of energy that will be generated in the next few days and therefore anticipate their energy consumption, as well as gives them the statistics of their consumption. After the first full year of using the proposed energy system, the users will be given an evaluation survey to address any issues and give feedback on the system.

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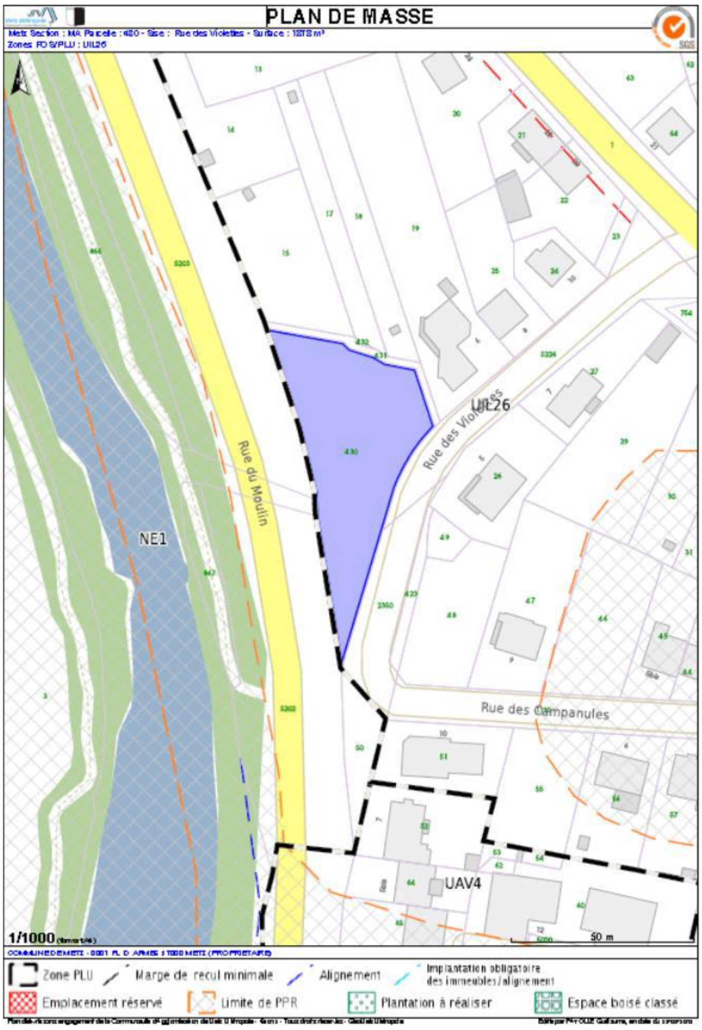
7. APPENDIXES

7.1. APPENDIX 1 – The lot



7.2. APPENDIX 2 – Weather data from RETscreen

	Unit	Climate data location	Facility location	Source
Latitude		49.1	49.1	
Longitude		6.1	6.2	
Climate zone		4A - Mixed - Humid		Ground+NASA
Elevation	m	192		Ground – Map
Heating design temperature	°C	-5.8		Ground
Cooling design temperature	°C	29.3		Ground
Earth temperature amplitude	°C	17.1		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	2.4	84.5%	67.89	0.97	98.6	3.4	-0.3	484	0
February	3.1	80.9%	56.28	1.73	98.6	3.4	0.5	417	0
March	6.7	75.0%	58.59	2.71	98.5	3.3	4.3	350	0
April	9.7	70.0%	52.80	3.96	98.2	3.2	8.3	249	0
May	14.4	70.8%	67.58	4.98	98.4	2.9	13.1	112	136
June	17.6	69.3%	66.90	5.22	98.5	2.8	16.5	12	228
July	19.5	69.5%	66.65	5.23	98.5	2.9	19.2	0	295
August	19.5	70.4%	63.86	4.54	98.5	2.6	19.2	0	295
September	15.0	78.0%	63.60	3.10	98.6	2.6	14.5	90	150
October	10.8	84.1%	71.30	1.79	98.5	2.9	9.5	223	25
November	6.0	87.2%	66.90	1.04	98.4	2.9	4.0	360	0
December	3.1	87.0%	80.60	0.75	98.6	3.5	0.8	462	0
Annual	**10.7**	**77.2%**	**782.95**	**3.01**	**98.5**	**3.0**	**9.2**	**2,759**	**1,128**
Source	Ground	Ground	NASA	NASA	NASA	Ground	NASA	Ground	Ground
Measured at					m	10	0		

7.3. APPENDIX 3 – Demand of Energy for Ambient Heating

Assumptions:

Size of apartments:

	Lateral 1 [m]	Lateral 2 [m]	Area [m²]
Single	8	5	40
Couple	10	6	60
Family of 3	8	10	80

Calculation parameters:

Heat pump efficiency	3	
Heat loss coefficient U	0.93	W/m²/ºC
Height of house	3	m
Area of heat loss (single)	79	m²
Area of heat loss (couple)	108	m²
Area of heat loss (family)	134	m²

Degrees-day of heat:

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days in the month	31	28	31	30	31	30	31	31	30	31	30	31
Degrees-day of Heat (considering 18ºC)	484	417	350	249	112	12	0	0	90	223	360	462

App. type	Hours at home	Surface	Heat Energy Consumption - electric [kWh]												TOTAL
	h/day	m²	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	kWh/year
Single 1	16.9	40	200	172	144	103	46	5	0	0	37	92	149	191	1139
Single 2	24.0	40	284	245	206	146	66	7	0	0	53	131	212	272	1622
Single 3	16.9	40	200	172	144	103	46	5	0	0	37	92	149	191	1139
Single 4	16.9	40	200	172	144	103	46	5	0	0	37	92	149	191	1139
Couple 1	16.9	60	273	235	198	141	63	7	0	0	51	126	203	261	1557
Couple 2	19.7	60	319	275	231	164	74	8	0	0	59	147	238	305	1821
Couple 3	16.9	60	273	235	198	141	63	7	0	0	51	126	203	261	1557
Couple 4	19.7	60	319	275	231	164	74	8	0	0	59	147	238	305	1821
Family 1	19.7	80	396	341	287	204	92	10	0	0	74	183	295	378	2259
Family 2	24.0	80	483	416	349	248	112	12	0	0	90	222	359	461	2751
Family 3	19.7	80	396	341	287	204	92	10	0	0	74	183	295	378	2259
TOTAL		640	3344	2881	2418	1721	774	83	0	0	622	1541	2488	3192	**19064**

7.4. APPENDIX 4 – Electricity and hot water demand

App. type	Hours at home	Surface	Electricity Cons.	Water Heating	TOTAL
	h/day	m²	kWh / month	kWh / year	kWh/year
Single 1	16.9	40	51.126	45.625	1161.0
Single 2	24.0	40	72.789	45.625	1421.0
Single 3	16.9	40	51.126	45.625	1161.0
Single 4	16.9	40	51.126	45.625	1161.0
Couple 1	16.9	60	61.4	91.3	1831.5
Couple 2	19.7	60	71.8	91.3	1956.4
Couple 3	16.9	60	61.4	91.3	1831.5
Couple 4	19.7	60	71.8	91.3	1956.4
Family 1	19.7	80	83.8	136.9	2648.3
Family 2	24.0	80	102.0	136.9	2866.9
Family 3	19.7	80	83.8	136.9	2648.3
TOTAL		640	762.1	958.1	**20643.2**

7.5. APPENDIX 5 – Equipment

7.5.1. APPENDIX 5.1 – Solar PV panel

Electrical data (STC)

		NU-AF370	
Maximum power	P_{max}	370	W_p
Open-circuit voltage	V_{oc}	48.82	V
Short-circuit current	I_{sc}	9.87	A
Voltage at point of maximum power	V_{mpp}	39.66	V
Current at point of maximum power	I_{mpp}	9.33	A
Module efficiency	η_m	19.0	%

STC = Standard Test Conditions: irradiance 1,000 W/m², AM 1.5, cell temperature 25 °C.
Rated electrical characteristics are within ±10% of the indicated values of I_{sc}, V_{oc} and 0 to +5% of P_{max} (power measurement tolerance ±3%).
Reduction of efficiency from an irradiance change of 1,000 W/m² to 200 W/m² (T_{module} = 25 °C) is less than 3%.

Electrical data (NMOT)

		NU-AF370	
Maximum power	P_{max}	276.5	W_p
Open-circuit voltage	V_{oc}	46.27	V
Short-circuit current	I_{sc}	8.0	A
Voltage at point of maximum power	V_{mpp}	37.02	V
Current at point of maximum power	I_{mpp}	7.47	A

NMOT = Nominal Module Operating Temperature: 45 °C, irradiance 800 W/m², air temperature of 20 °C, wind speed of 1 m/s.

Mechanical data

Length	1,960 mm
Width	992 mm
Depth	40 mm
Weight	22.5 kg

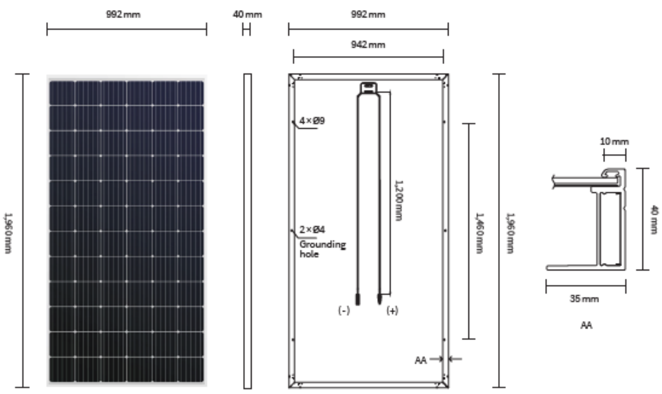
Temperature coefficient

P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

Limit values

Maximum system voltage	1,000 VDC
Over-current protection	15 A
Temperature range	-40 to +85 °C
Max. mechanical load (snow/wind)	2,400 Pa
Tested snow load (IEC61215 test pass*)	5,400 Pa

Dimensions (mm)



*Please refer to Sharp's installation manual for details.

Packaging data

Modules per pallet	27 pcs
Pallet size (L × W × H)	2.000 m × 1.050 m × 1.280 m
Pallet weight	650 kg

General data

Cells	Monocrystalline silicon 157 mm × 157 mm, 72 cells in series
Front glass	Anti-reflective high transmissive low iron tempered glass, 3.2 mm
Frame	Anodized aluminium alloy, silver
Connection box	IP67 rating, 3 bypass diodes
Cable	Diameter 4.0 mm², length 1,200 mm
Connector	MC4 (Multi Contact, Stäubli)

Note: Technical data is subject to change without prior notice. Before using Sharp products, please request the latest data sheets from Sharp. Sharp accepts no responsibility for damage to devices which have been equipped with Sharp products on the basis of unverified information. The specifications may deviate slightly and are not guaranteed. Installation and operating instructions are to be found in the corresponding handbooks, or can be downloaded from www.sharp.eu. This module should not be directly connected to a load.

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7.5.2. APPENDIX 5.2 – Electrolyser H2B2 EL10N

H2B2

Main Characteristics	EL10N
Electrolysis Type	PEM (Proton exchange membrane, caustic free)
Number of Cell Stacks	1
Hydrogen Gas Production	
Max. Nominal Hydrogen Flow	10.05 Nm^3/h (21.68 kg/day)
Hydrogen Flow Range	10 -100%
Operating Pressure	15 - 40 barg (217-580 psig)
Hydrogen Purity (before Gas Purification)	> 99.9% ; < 25 ppm O_2; H_2O saturated
Hydrogen Purity (after Gas Purification)	99.999%; < 5 ppm O_2; < 5 ppm H_2O
Electrical Requirements	
Voltage	3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)
Frequency	50 Hz ± 5% / 60 Hz ± 3%
Power (BoP + Stack)	53.2 kW
Stack Consumption (*)	4.7 kWh/Nm^3 H_2
AC Power Consumption (BoP + Stack) (*)	5.3 kWh/Nm^3 H_2
Feed Water - Tap Water (if Water Treatment Plant is included)	
Consumption	< 20.1 L/h
Conductivity	< 2,000 uS/cm (T 25 °C (77 °F))
Pressure	2-6 barg (29-87 psig)
Temperature	+5 °C to +40 °C (+41 °F to +104 °F)
Feed Water - Demi Water (if Water Treatment Plant is not included)	
Consumption	< 1 L/Nm^3 H_2
Quality	> 10 MΩcm (< 0.1 uS/cm); TOC < 30 ppb
Control System	
PLC	Fully automated and unattended with 7" color touch screen
Communication	Modbus TCP/IP or Profinet (RJ45 port)
Environmental Conditions	
Ambient Temperature Range	+5 °C to +45 °C (+41 °F to +113 °F)
Humidity	0 to + 95% (non-condensing)
Air Ventilation	Available from a non-hazardous area
Installation Area	Indoor/Outdoor
Dimensions and weight	
Dimensions (LxWxH)	10 ft container (3.0m x 2.4m x 2.9m) (9.8ft x 7.9ft x 9.5ft)
Approx. Weight	5,000 kg (11,023 lb)
Standards & Regulations	
Compliance	CE, ISO 22734-1 / NFPA 2-2016 & NFPA 70
Other Characteristics	
Duty Cycle	100% (24/7)
Start-up Time (from Stand-by)	< 1 sec
Cold Start Time	< 5 min
Nitrogen System	For each purge, consumption is <0.1 kg at 3 barg (to be supplied by the customer)
Instrumentation Air System	Consumption 4 Nm^3/h at 10 barg (to be supplied by the customer)

(*) Electrical consumption at maximum current density and operating pressure at the stack; thus is reduced if those are not required.

Included	Additional Options
Hydrogen Cooling System	Oxygen Processing System
Emergency Shutdown System	Hydrogen Purification System (SAE J2719 September 2011)
Overpressure Relief System	Water Treatment System
Redundancy on Critical Safety Parameters	Extreme Environmental Conditions Package (Low and High Temp)
Uninterruptible Power Supply (UPS)	Hydrogen Mass Flow Measure & Purity Measure (H_2O & O_2 Sensors)
Heat Management (No Cooling Water is Needed)	Instrumentation Air System
Virtual Private Network (VPN) connection	Nitrogen System

7.5.3. APPENDIX 5.3 – Storage tank

STEELHEAD COMPOSITES COMPRESSED GAS CYLINDERS

SPECIFICATIONS

- Type 3 Pressure Vessel
- Maximum Operating Pressure: 5,000 psi (345 bar)
- Minimum Burst Pressure: 15,000 psi (1,034 bar)
- Port Opening: up to 2 inches (51 mm) in diameter
- Safety: Benign leak-before-burst avoids catastrophic failure
- Compliant with US/DOT and UN/ISO 11119-2 requirements
- Liner: Seamless, impermeable 6061-T6 Aluminum
- Structural Shell: Carbon fiber and epoxy composite
- Protective Barrier: Glass fiber and epoxy composite
- Neck or strap mounting available
- High thermal conductivity of Aluminum liner achieves a better fill capacity under fast-fill conditions
- Corrosion Resistant: Not prone to rusting like steel

A=9.2 m ; B=3 m ; 0.1 m thickness.
The price for 12000 gallons (45m^3) estimated for the website Matches Equip-cost.

7.5.4. APPENDIX 5.4 – Compressor

There is a slight difference of price we used, due to be accessed it earlier.

Product Paramenters

Brand model number	TRD-H-W	
medium	Air	
Working pressure/Optional	200bar/300bar	
Ultimate Pressure Safety Valve	225bar/330bar	
Filter model	DIN EN 12021/P21	
Number of cylinders	3	
flow/Min3	140L/Min3	
Noise / dB	78/db	
Lubricant oil and Refueling capacity	0.75/L	
Drive way	Single phase motor/220V	The three-phase motor/380V
Power frequency	2.2KW/50HZ	3KW/50HZ
Rotating speed/ minute	2850/MIN	2850/MIN
weight	65KG	70KG
physical dimension	Length/85cm	wedth/40cm
Fill time	0-200bar/10L/20min	0-300bar/6.8L/20min

7.5.5. APPENDIX 5.5 – Fuel cell

EKPO FUEL CELL TECHNOLOGIES

BENEFITS

- / High power density due to lightweight, compact stack design
- / High dynamic response in power provisioning
- / Robust component and stack design suitable for mass production, with long service life and minimal power degradation
- / Proven cold-start performance and durability
- / System simplification by integration of functions at the media supply assembly of the stack (sensors, actuators and valves)
- / Metallic bipolar plates in patented designs

SPECIFICATIONS

GENERAL DATA

Cell Count	335
Rated stack power	76 kW
Power density stack[1]	3.6 kW/l
Power density cell block[2]	4.6 kW/l
Rated stack voltage	201 V
Rated current[3]	380 A (2.0 A/cm²)
Rated operation pressure	2.5 bar_a
Active area	190 cm²
Cell pitch	1.34 mm
Orientation	cells vertical
Dimension incl. housing [mm]	329x225x687 mm

[1] value refers to cell row assembly including compression hardware
[2] based on bipolar plate contour
[3] current at 0.6 V cell voltage

7.5.6. APPENDIX 5.6 – Battery module

BATTERY-BOX PREMIUM LVS

- Scalable from 4 kWh to 256 kWh
- Maximum Flexibility for any Application with up to 64 Modules Connected in Parallel
- Compatible with Market Leading 1 and 3 Phase Inverters
- Cobalt Free Lithium Iron Phosphate (LFP) Battery: Maximum Safety, Life Cycle and Power
- Capable of High-Powered Emergency-Backup and Off-Grid Function
- Patented Internal Plug Design Requires No Additional Wiring
- Self-Consumption Optimization for Residential and Commercial Applications

BATTERY-BOX PREMIUM LVS

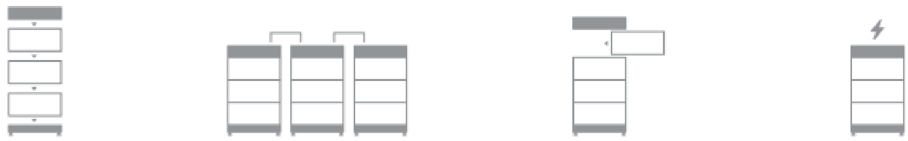
- 4 kWh Module
- Modular Design Simplifies Transport and Installation

The BYD Battery-Box Premium LVS is a lithium iron phosphate (LFP) battery pack for use with an external inverter. A single Battery-Box Premium LVS contains between 1 to 6 battery modules LVS stacked in parallel and can reach 4 to 24.0 kWh usable capacity in one tower:

- Battery-Box LVS 4.0 (4 kWh)
- Battery-Box LVS 8.0 (8 kWh)
- Battery-Box LVS 12.0 (12 kWh)
- Battery-Box LVS 16.0 (16 kWh)
- Battery-Box LVS 20.0 (20 kWh - single tower only)
- Battery-Box LVS 24.0 (24 kWh - single tower only)

Connect up to 16 Battery-Box LVS 16.0 in parallel for a maximum size of 256 kWh. Ability to scale by adding LVS modules or parallel towers of 1 to 4 modules later.

FLEXIBLE, EFFICIENT, SIMPLE



Internal Plug Connection
No Additional Wiring Required

4 - 256 kWh
Tailored Sizing for Each Application

Extend Anytime
Easily Adapts to New Requirements

High Power
Power for Every Application

TECHNICAL PARAMETERS **PREMIUM LVS**

	LVS 4.0	LVS 8.0	LVS 12.0	LVS 16.0	LVS 20.0	LVS 24.0
Battery Module	LVS (4 kWh, 51.2 V, 45 kg)					
Number of Modules	1	2	3	4	5	6
Usable Energy [1]	4 kWh	8 kWh	12 kWh	16 kWh	20 kWh	24 kWh
Max Cont. Output Current [2]	65 A	130 A	195 A	250 A	250 A	250 A
Peak Output Current [2]	90 A, 5 s	180 A, 5 s	270 A, 5 s	360 A, 5 s	360 A, 5 s	360 A, 5 s
Dimensions (H/W/D)	528 x 650 x 298 mm	761 x 650 x 298 mm	994 x 650 x 298 mm	1227 x 650 x 298 mm	1460 x 650 x 298 mm	1693 x 650 x 298 mm
Weight	64 kg	109 kg	154 kg	199 kg	244 kg	289 kg
Nominal Voltage	51.2 V					
Operating Voltage	40-57.6 V					
Operating Temperature	-10 °C to +50°C					
Battery Cell Technology	Lithium Iron Phosphate (cobalt-free)					
Communication	CAN / RS485					
Enclosure Protection Rating	IP55					
Round-Trip Efficiency	≥95%					
Scalability [3]	Max. 64 Modules in Parallel (256 kWh)				Single Tower Only	
Certification	VDE2510-50 / IEC62619 / CE / CEC / UN38.3					
Applications	ON Grid / ON Grid + Backup / OFF Grid					
Warranty [4]	10 Years					
Compatible Inverters	Refer to BYD Battery-Box Premium LVS Minimum Configuration List					

[1] DC Usable Energy, Test conditions: 100% DOD, 0.2C charge & discharge at + 25 °C. System Usable Energy may vary with different inverter brands
[2] Charge derating will occur between -10 °C and +5 °C
[3] Parallel tower function only available for 1 to 4 battery modules per tower. LVS 20.0 and LVS 24.0 can only be used as a single tower.
[4] Conditions apply. Refer to BYD Battery-Box Premium Limited Warranty Letter.

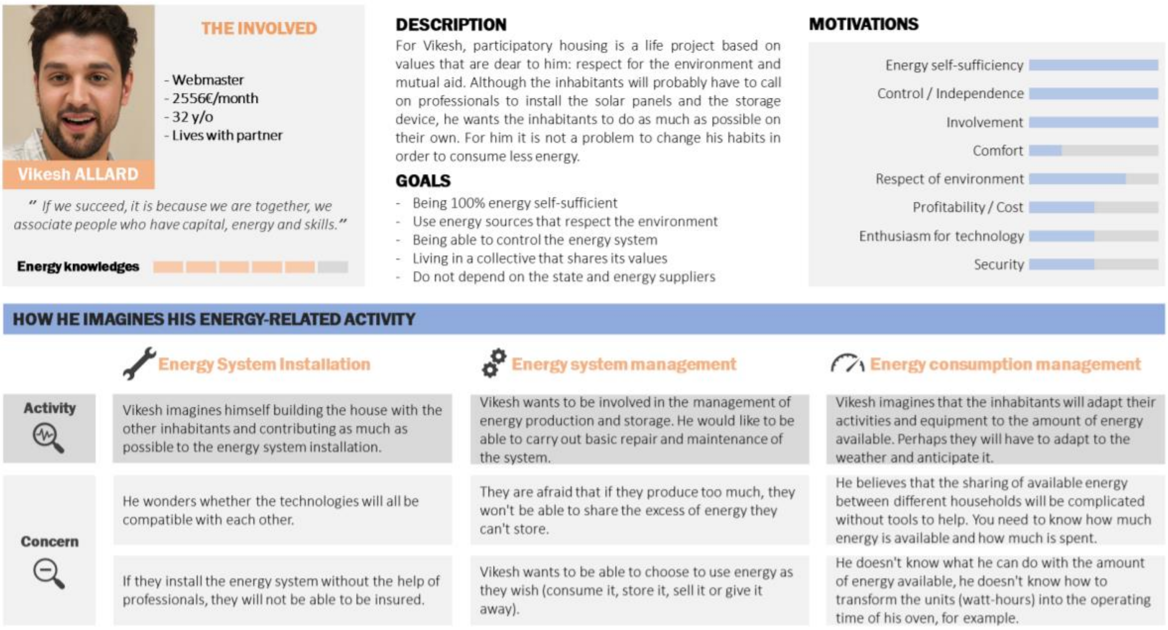
7.5.7. APPENDIX 5.7 – Inverter

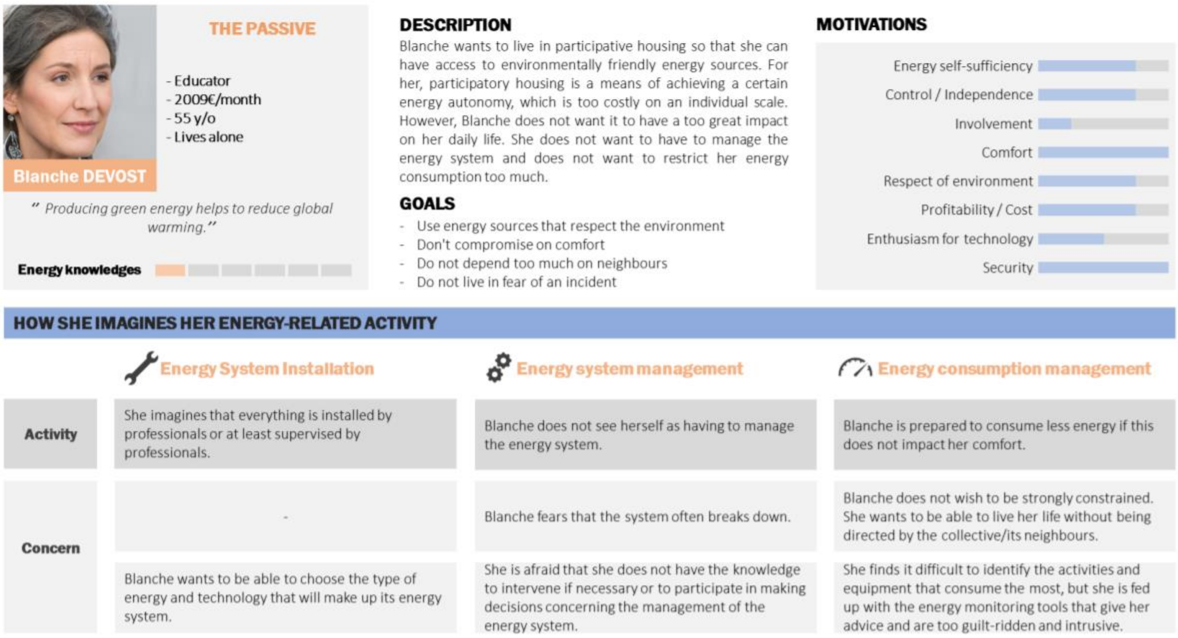
MT Series Datasheet

Technical Data	GW50KN-MT	GW60KN-MT	GW50KBF-MT	GW60KBF-MT	GW75KBF-MT	GW80KBF-MT
DC Input Data						
Max. PV Power (W)	65000	80000	65000	80000	97500	104000
Max. DC Input Voltage (V)	1100	1100	1100	1100	1100	1100
MPPT Range (V)	200~1000	200~1000	200~1000	200~1000	200~1000	200~1000
Starting Voltage (V)	200	200	200	200	200	200
Min. Feed-in Voltage (V)	210	210	210	210	210	210
Nominal DC Input Voltage (V)	620	620	620	620	750	800
Max. Input Current per MPPT (A)	33/33/22/22	33	30	44	44	39
Max. Short Circuit Current per MPPT (A)	41.5/41.5/27.5/27.5	41.5	37.5	55	55	54.8
No. of MPP Trackers	4	4	4	4	4	4
No. of Input Strings per Tracker	3/3/2/2	3	2	3	3	3
AC Output Data						
Nominal Output Power (W)	50000	60000	50000	60000	75000	80000
Max. AC Active Power (cosφ=1)	55000;57500 @415Vac*[1]	66000;69000 @415Vac*[1]	55000;57500 @415Vac*[1]	66000;69000 @415Vac*[1]	82500*[1]	88000*[1]
Max. Output Apparent Power (VA)	55000;57500 @415Vac*[2]	66000;69000 @415Vac*[2]	55000;57500 @415Vac*[2]	66000;69000 @415Vac*[2]	82500*[2]	88000*[2]
Nominal Output Voltage (V)	400, default 3L+N+PE, 3L+PE optional in settings				500, 3L/PE	540, 3L/PE
Nominal Ouput Frequency (Hz)	50/60	50/60	50/60	50/60	50/60	50/60
Max. Output Current (A)	80	96	80	96	95.3	94.1
Output Power Factor	~1 (Adjustable from 0.8 leading to 0.8 lagging)					
Output THDi (@Nominal Output)	<3%	<3%	<3%	<3%	<3%	<3%
Efficiency						
Max. Efficiency	98.7%	98.8%	98.8%	98.8%	99.0%	99.0%
European Efficiency	98.3%	98.5%	98.3%	98.3%	98.4%	98.4%
Protection						
PV String Current Monitoring	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Anti-Islanding Protection	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Input Reverse Polarity Protection	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Insulation monitoring	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
DC fuse	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Anti-PID Function for Module	Optional	Optional	Optional	Optional	Optional	Optional
DC Surge Arrester	Integrated (Type II)					
AC Surge Arrester	Integrated (Type II)					
Residual Current Monitoring Unit	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
AC Over Current Protection	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
AC Short Circuit Protection	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
AC Over Voltage Protection	Integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Humidity Monitoring	-	-	-	NA	NA	NA
General Data						
Ambient Temperature Range (°C)	-30~60	-30~60	-30~60	-30~60	-30~60	-30~60
Relative Humidity	0~100%	0~100%	0~100%	0~100%	0~100%	0~100%
Operating Altitude (m)	≤4000	≤4000	≤4000	≤4000	≤4000	≤4000
Cooling	Fan Cooling	Fan Cooling	Fan Cooling	Fan Cooling	Fan Cooling	Fan Cooling
Display	LCD or WiFi+APP			LED, WiFi+APP		
Communication	RS485 or WiFi or PLC					
Weight (kg)	59	64	60	65	65	65
Dimension (Width*Height*Depth mm)	586*788*264	586*788*264	586*788*264	586*788*267	586*788*267	586*788*267
Protection Degree	IP65	IP65	IP65	IP65	IP65	IP65
Night Self Consumption (W)	<1	<1	<1	<1	<1	<1
Topology	Transformerless					

*[1]: For Belgium Max. Output Power (W): GW50KN-MT is 50000; GW60KN-MT is 60000; GW50KBF-MT is 50000; GW60KBF-MT is 60000; GW75KBF-MT is 75000; GW80KBF-MT is 80000.
*[2]: For Belgium Max. Output Apparent Power (VA): GW50KN-MT is 50000; GW60KN-MT is 60000; GW50KBF-MT is 50000; GW60KBF-MT is 60000; GW75KBF-MT is 75000; GW80KBF-MT is 80000.
*: Please visit GoodWe website for the latest certificates.

7.6. APPENDIX 6 – Personas – The Involved and The Passive





7.7. APPENDIX 7 – Surveys

Survey 1 – Users' Needs:
https://docs.google.com/forms/d/1V7KMgxWJTcNia6IDoQzKJsKIIYhKi8iAwXjaWZ0emgY/edit
Survey 2 – Evaluation:
https://docs.google.com/forms/d/1-Nz1EIx-xa1XZimZvmNDvjn0P7T0c7GtSbBpODJ-qvU/edit?