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Modelling tools for the techno-economic optimization of energy storage solutions for remote applications

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In collaboration with:

SINTEF

REMOTE

Remote area Energy supply with Multiple Options for
integrated hydrogen-based TEchnologies

Abstract

In remote locations, it could be difficult or overly expensive to have a connection to the electric grid. In these situations, in particular, in the case of small communities, it is preferable to have autonomous grids which can be supplied by diesel generators, which guarantee good reliability and availability. An alternative solution could be the adoption of technologies using renewable sources (e.g. PV panels, wind turbines, biomass). However, due to the fluctuation of some sources, it is necessary to have storage systems which can make up to periods with low or null production, or which can cover the load peaks avoiding the oversizing of the equipment. A possible solution can be a hybrid system which uses both batteries and hydrogen to store energy. This solution is proposed by the Remote (Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnology) project which studies the feasibility of these kinds of systems for the energy autonomy of isolated locations. In these situations, it could be convenient or preferable using renewable and clean sources rather than fossil fuels, because the connection to the grid could be complicated from a logistic and also an economic point of view.

The P2P system consists of an electrolyser, which stores energy in the form of hydrogen, and in a fuel cell which uses the hydrogen to give back energy when is necessary. Although P2P systems are quite expensive at the moment, they allow storing a significant quantity of energy for a long time avoiding oversizing of batteries.

Inside the Remote project, an optimisation method it was studied for the sizing of these kind of systems from a techno-economical point of view. The model developed by SINTEF, called HyOpt, consists of three parts: an Excel front end, an SQLite database, and the optimisation model itself, written in the FICOTM Mosel optimisation language. The SINTEF's purpose is to make this model usable to professional users who are considering the realisation of a hybrid system. For this reason, the first part of the work focused on the implementation of a simpler interface reorganising the Excel file, from which the code reads the data needs and on which results are displayed. Through this work, the necessary input information has been reduced, and the output part has been changed. In these sheets, we can find several charts, panels and tables reporting the principal economic results, useful to compare the system, and other information about the operation of the components.

After that, the method has been applied to a site exanimated by KTH University of Stockholm. The case study regards the realisation of a hybrid system on the Kökar island, one of the Åland Islands, a Finnish archipelago in the Baltic Sea. Several possible configurations have been considered, and the results have been compared to each other.

Abstract (ita)

In località remote può essere difficoltoso o eccessivamente oneroso riuscire ad avere un collegamento con la rete elettrica. In queste situazioni, soprattutto in caso di piccole comunità, è preferibile avere delle reti indipendenti che possono essere alimentate da generatori diesel, i quali garantiscono una buona affidabilità e continuità del servizio. Un'alternativa può essere quella di adottare delle tecnologie che sfruttino le risorse rinnovabili presenti sul territorio (per esempio pannelli fotovoltaici, turbine eoliche, biomassa). Tuttavia, a causa della discontinuità di certe fonti, è necessario avere dei sistemi di stoccaggio che sopperiscano ai momenti in cui la produzione è scarsa o assente, o possano coprire i picchi di richiesta senza che sia necessario un sovradimensionamento degli impianti. Una possibile soluzione può essere quella di adottare un sistema ibrido che utilizzi come tecnologie per lo stoccaggio batterie e idrogeno allo stesso tempo. Questa è la soluzione che si propone con il progetto *Remote* che studia la fattibilità di questi sistemi per l'autosufficienza di località isolate dove è conveniente o preferibile utilizzare fonti rinnovabili e pulite di energia piuttosto che fonti fossili. Inoltre, in questi siti, può essere complicato, da un punto di vista logistico o economico, approvvigionarsi dalla rete.

La presenza di un sistema P2P (power to power), che immagazzini energia sotto forma di idrogeno tramite un elettrolizzatore e la renda disponibile quando necessario grazie a una fuel cell, permette, seppur in genere più oneroso di uno con sola batteria, di stoccare relativamente grandi quantità di energia per lunghi periodi evitando un sovradimensionamento delle batterie.

Con il progetto *Remote* è stato studiato un metodo per ottimizzare il dimensionamento di questi sistemi da un punto di vista tecno-economico. Il modello sviluppato da SINTEF, chiamato HyOpt, è composto da tre parti: un file Excel, un database SQLite e il modello vero è proprio realizzato in linguaggio FICO™ Mosel. Il fine di SINTEF è di rendere fruibile questo modello ad utilizzatori professionali che siano interessati a considerare la realizzazione di un proprio sistema ibrido. Per questo motivo, la prima parte del lavoro si è concentrata sulla realizzazione di un'interfaccia più semplificata riorganizzando il file Excel, da cui il codice legge i dati necessari e sul quale vengono visualizzati i risultati. In questo modo, sono state ridotte le informazioni necessarie da inserire ed è stata curata la parte di output. In quest'ultima troviamo una serie di grafici, tabelle e pannelli riportanti i principali risultati economici utili a comparare il sistema, e altre informazioni legate al funzionamento dei vari elementi.

Successivamente, il metodo è stato applicato a un sito in esame all'università KTH di Stoccolma. Il caso studio riguarda la realizzazione di un sistema ibrido presso l'isola di Kökar, nelle isole Åland, un arcipelago della Finlandia situato nel Mar Baltico. Sono state considerate varie possibili configurazioni del sistema e i risultati sono stati comparati fra loro.

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1. Introduction

1.1 Motivation

In various situations, the access to the electricity grid is not available due to technical or economic reasons. For example, in remote locations like islands, mountains or regions with a low population density, an alternative solution can be preferable. According to IEA [1], the number of people without electricity access is sharply reduced from 1.7 billion in 2000 to 1.1 billion in 2016. However, about 14% of the world's population still lacks access to electricity and 84% of which lives in rural areas. The previous improvement was possible mainly thanks to the grid extensions (97%) but, due to the renewable and storage costs reduction, decentralised renewable energy systems are becoming the best solution for isolated communities. In particular, we distinguish two types of decentralised systems:

- *Off-grid systems*: they are stand-alone systems, not connected to the grid, which typically supply a single house. For example, they can be diesel generators or PV systems installed on the roof of the buildings. In this last case, PV panels are usually coupled with batteries to counteract the source's fluctuations.
- *Micro-grid systems*: they are systems bigger than the previous, which usually serve small communities located in remote areas. In this case, energy can be produced in several ways, for example, using diesel generators, PV, wind turbines. In renewable-based microgrids, to have a back-up system, like a diesel generator or a storage system (battery, hydrogen etc.); is necessary.

According to IEA scenario [1], the number of people without access to electricity will fall by 36% by 2030, despite an increase of population, and the universal access will be achieved in some country (Figure 1.1).

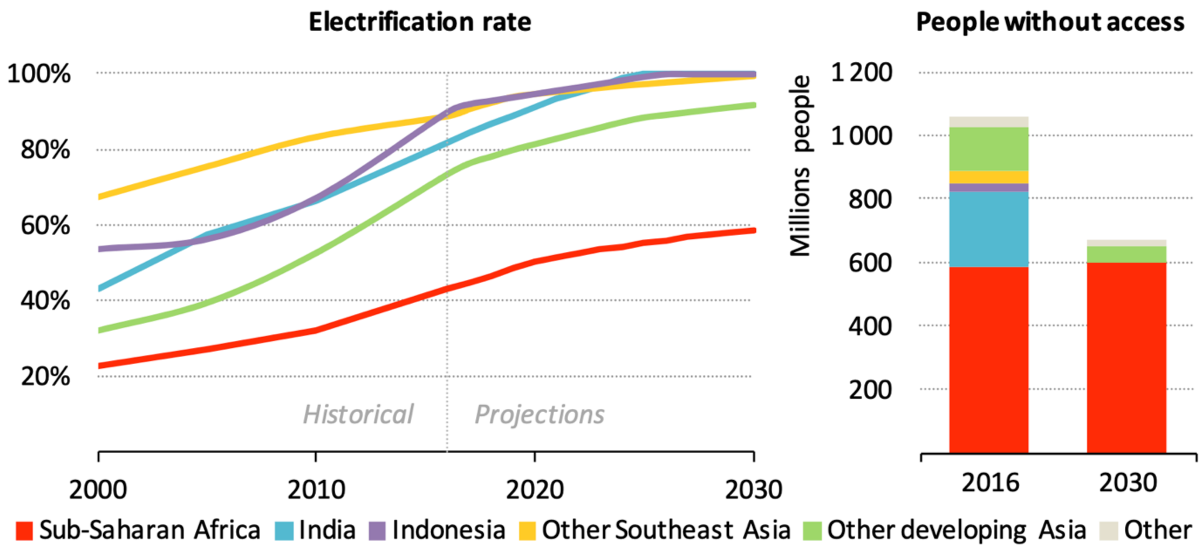

Figure 1.1: Electricity access rate and population without electricity by region in the IEA New Policies Scenario [1]

As reported in the IEA report, the centralised power grid extension will remain the primary way for electrification because it is usually the least-cost option, but about half of people will gain access thanks to decentralised solutions (Figure 1.2). In particular, this portion increases over two-thirds in rural locations. Furthermore, the share of fossil fuels as sources for electricity production will decline both for grids and especially for decentralised solutions, since more than 60% of those who will gain access through off-grid and micro-grid systems will do so with electricity generated from renewables [1].

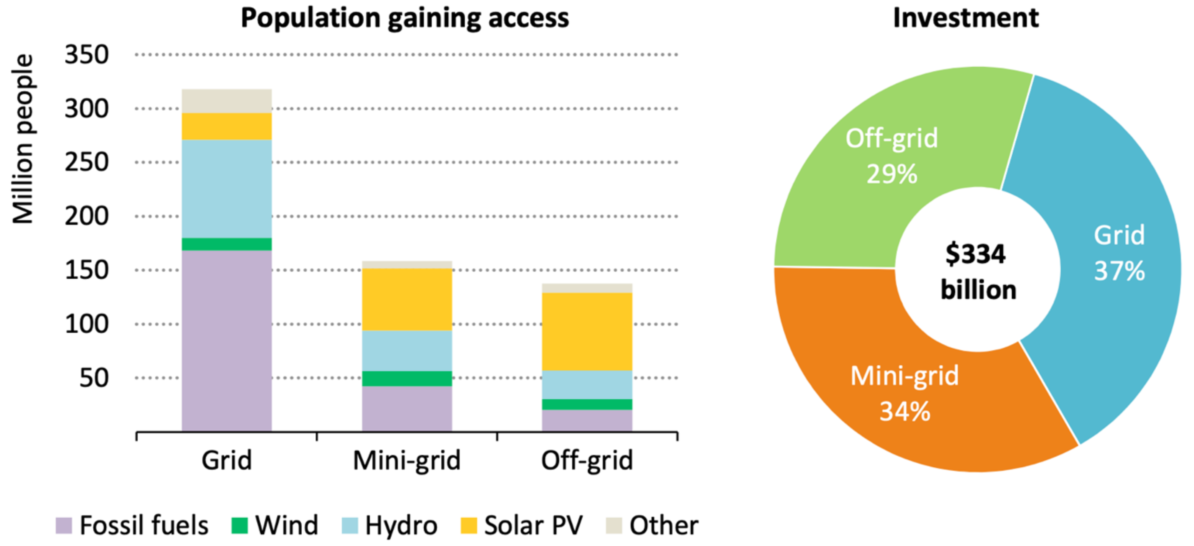

Figure 1.2: Cumulative population gaining access to electricity and cumulative investment in the New Policies Scenario, 2017-2030 [1]

In fact, for remote areas, decentralised solutions could be cheaper than a grid extension, though the electricity cost for people living in these areas is higher than for people served by the grid in urban locations. As we can see below (Figure 1.3), for mini-grid and off-grid systems, the Levelized Cost of Electricity (LCOE) using renewable sources would be lower than using diesel generators.

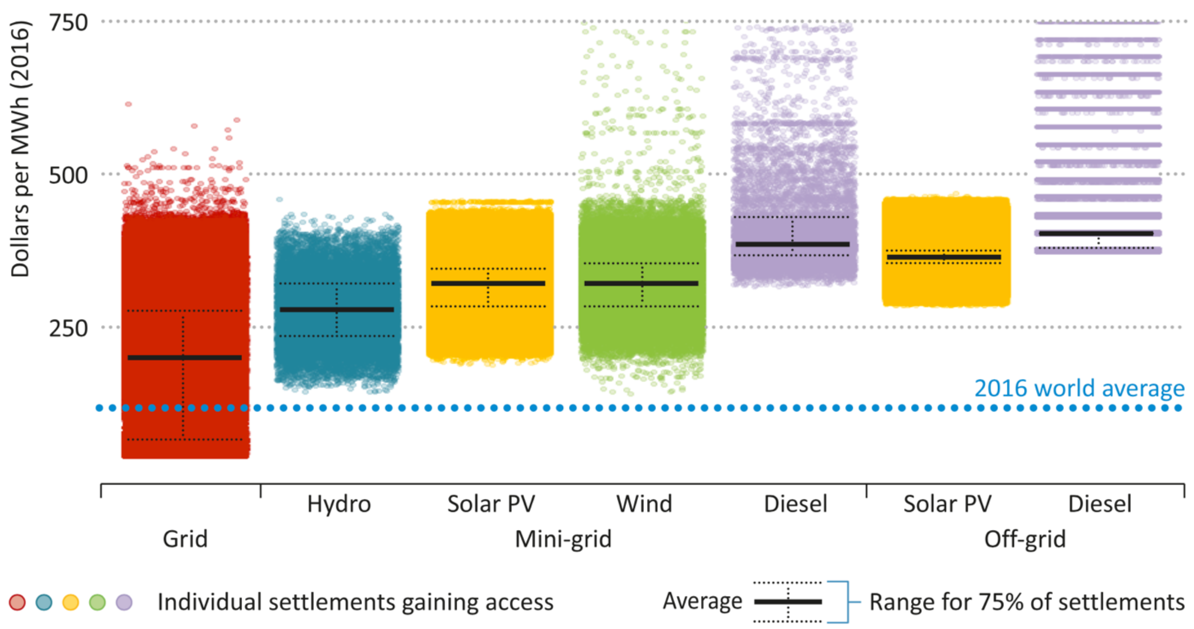

Figure 1.3: Levelized cost of electricity (LCOE) for electricity access solutions in the New Policies Scenario to 2030 [1]

If we consider the total investment for providing electricity according to this scenario, the total cumulative investment would be around 334 billion over the period to 2030 (1,5% of global investment in the energy sector) and almost 90% of all investment in generation is for renewables.

However, 674 million people (8% of the world's population in 2030) will not have access to electricity yet by 2030, 90% of which will be in rural areas. Assuming to provide access also for these people by 2030, the role of decentralised systems and renewables would become crucial. Over 485 million (72% of the additional people) would have access to electricity through decentralised systems, 290 millions of which trough micro-grids. At the same time, PV would be the principal sources considering the availability of solar power in these regions (602 million people who would gain access live in Africa) [1]. The additional investment would be slightly higher than the investment already considering in the previous scenario, but the share for decentralised systems would be higher as we can see in Figure 1.4, with almost half of the amount used for mini-grid realisation.

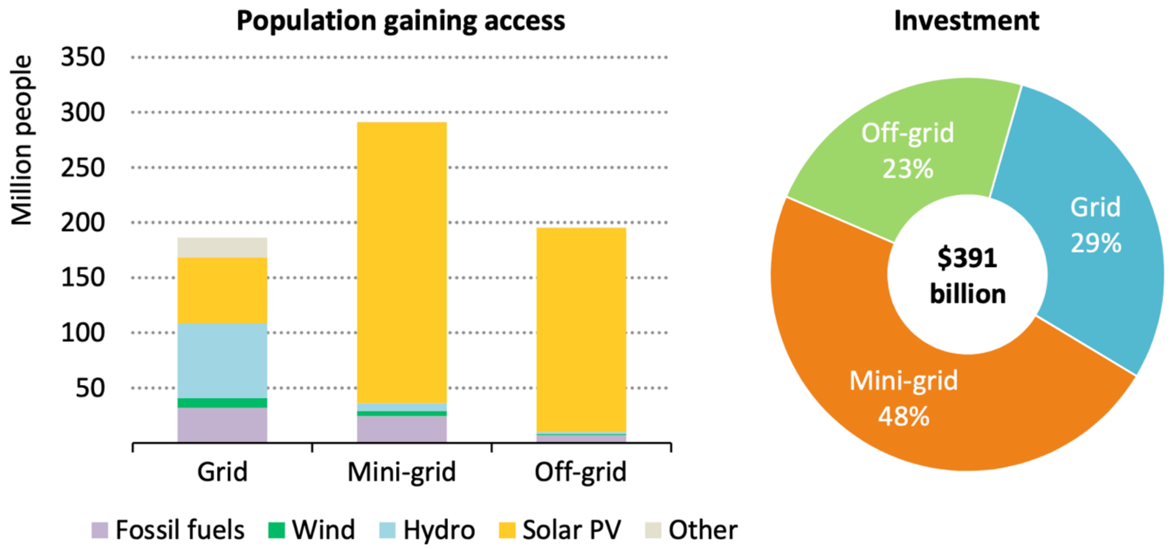

Figure 1.4: Additional population gaining access and additional investment in the Energy for All Case relative to the New Policies Scenario, 2017-2030 [1]

The interest for decentralised energy systems also regards other special applications in fields like telecommunication, earth satellite stations [2] or remote military camps [3]. For example, the widening of telecommunications networks brings to the installation of new remote base stations, like telecom towers. These installations request a constant supply of power 24 hours a day [4], so reliable systems endowed of back-up are necessary to avoid service interruption, also considering how difficult can be to reach the installation to fix it. In this field, there is a growing interest in the use of renewable power sources to replace old diesel generators. According to some estimates, 400,000 new telecom base stations using renewables could be built by 2020 with an associated market size of $10.5 billion p.a. [4] [5]

1.2 Aim of the work

The present Master Thesis has been carried out during an internship at SINTEF in Trondheim, Norway. The main aim of this work was to develop, in collaboration with SINTEF, a publicly available tool to calculate the optimal sizing of hybrid systems for remote application. SINTEF is working together with Politecnico di Torino and other partners on an EU-funded project called *Remote* (Remote area Energy supply with Multiple Options for integrated hydrogen-based TEchnology). This project aims to demonstrate the technical and economic feasibility of H2-based energy storage solutions installing four DEMO plants in either isolated micro-grids or off-grid remote areas of northern and southern Italy (Ambornetti and Ginostra), Greece (Agkistro), Norway (Froan island) [6]. The four sites use a different mix of renewable sources, which almost complete substituted fossil fuel, joined with hydrogen-battery hybrid systems as a back-up. SINTEF developed a techno-economic methodology to find the optimal composition, dimensioning and operation of these systems, minimising the NPC (Net Present Value).

The tool developed during this internship originates from SINTEF's optimisation model, HyOpt, programmed in Mosel language. The aim was to obtain a downloadable spreadsheet which, in combination with the code, can be used by professional customers interesting to install their own plants.

The developed tool has been validated through the analysis of a new case study in Kökar, in the Åland Islands, Finland. This site holds the characteristics to be a good location for a hydrogen-battery hybrid system, as it is far from the mainland and the on-site renewable sources can be exploited. Several scenarios have been explored to verify the model operation with different conditions.

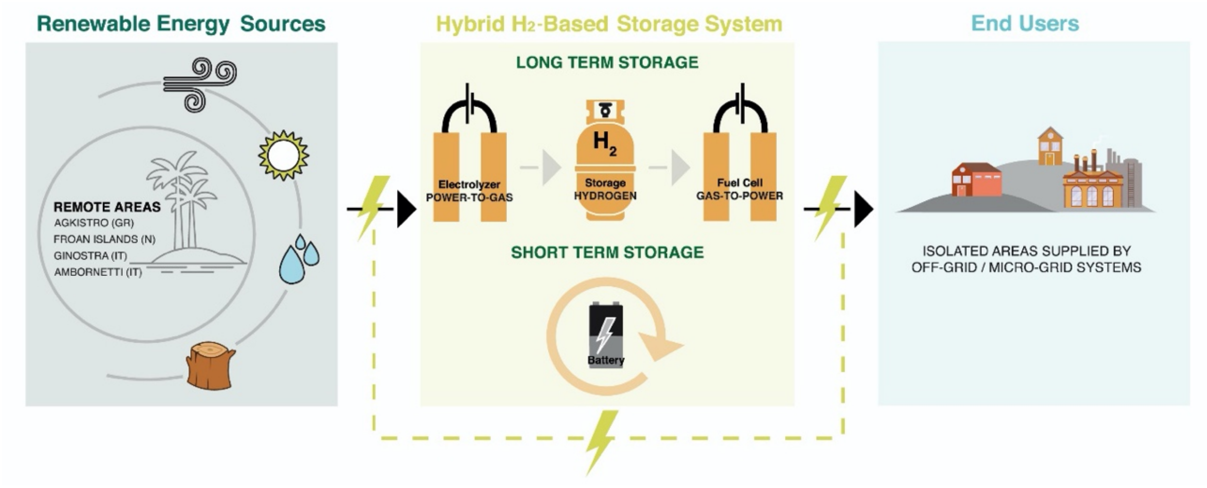

Figure 1.5: Schematic of the Remote's systems configuration [6]

2. Hybrid systems for remote applications

Diesel generators were the most diffused choice for electricity generation in remote off-grid locations, where it is not possible to connect to the grid. The use of this technology leads to high electricity generation cost. For example, in Italy, there are several islands not connected to the grid where the energy is produced by fossil fuel. The average generation cost in these islands is 0.39 €/kWh while, in the rest of Italy, the cost is six times lower (0.065 €/kWh) [7]. Thanks to aids to local plants, the electricity price for the inhabitants is almost the same than in the rest of the country, but the amount of money for these economic aids are taken by the electricity bill of all the Italians. The reason for the high generation cost is linked to the low efficiency of generators. They have to work always to guarantee the service, also if the load is very low, but it is not possible to have a fine regulation. These machines are also sized to cover the peak load, but the demand is lower for the majority, and so the fuel used is greater than necessary. Another important cause of the high cost is the transport of the fuel. The fuel necessary for the plants is not usually available in these locations, so it must be delivered to remote places but, due to the difficulty to reach them, the transportation can be costly. Furthermore, systems based only on Diesel generator are not enough reliable for some application, like telecommunication which, as we have seen before, must be available 24 hours in a day. Due to the location, it could be not possible to fix it in a short time these systems and, for this reason, it could be convenient to integrate a back-up ready to take over in case of malfunctions. Further problems of the Diesel generators for telecommunication are the risk of fuel theft and degradation [4]. Finally, the environmental impact of fossil fuel burning cannot be ignored, considering the constraints that governments must respect to reduce emission of pollutants and greenhouse gases.

For these reasons, the interest in systems which are supplied by renewable is increasing. If the site has good availability of renewable resources, this choice may be the most convenient. In the next paragraph, we will see the configuration of systems called *Hybrid Renewable Energy Systems* (HRES), which usually combine more than one renewable source with a back-up system to supply electricity in remote localities.

2.1 Configuration

HRES is composed of one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in stand-alone or grid-connected mode [8]. In these systems, especially for stand-alone applications in remote locations, we can consider primary sources of energy, which are intermittent renewable sources (solar, wind, hydropower…) and back-up devices (Diesel generator, battery, fuel cell…) which ensure electricity for the utility also when that from renewable is not sufficient to meet the load. The choice of technology for the primary source depends on what is locally available. The most common alternatives are PV panels, wind turbines, micro-hydro turbine or generator using biomass or biogas.

There are several advantages of using a hybrid system concerning a single-technology-based one [9]:

- Minimisation of the energy storage requirement: using two or more sources is possible to have more energy available and possibly in different periods, avoiding installing too big storage devices which can result expensive and inefficient.
- Increase of the reliability of power supply: availability of more sources and also back-up devices allow systems to supply electricity also in case of inadequate supplies by a source or in case of failures.
- Increase the quality of power.

Diesel generators can be used as back-up systems, but this could not be the best option due to the issues analysed in the previous paragraph. However, if the total available quantity of energy from renewable sources is not sufficient, a generator based on fossil fuel could be necessary. There are a wide variety of technologies which can be adopted as a back-up device. It can be useful to install more than one technology because they could be complementary and could have different roles in the systems. For example, there are devices which can supply a big amount of power quickly for short periods but cannot store a lot of energy, and others which can ensure to store a large quantity of energy for a long time. Storage systems are also useful in peak shaving, smoothing out load fluctuations, making up for intermittent variation in renewable energy sources so as to make efficient energy management in integrated systems [9]. Depending on the profile of the load and on the availability of the sources, storage system work in three different modes [9]:

- Charging: In this mode, energy generation at a particular instant is more than demand at that instant. Energy storage systems store the excess amount of energy and maintain energy balance to assure good power quality.
- Store: In this mode, energy generation is nearly equal to demand, and energy storage systems store the energy.
- Discharging: In discharging mode, generation is deficit and not able to meet the load demand. Storage systems provide energy to make up for the energy deficit.

It is also possible to have a classification of the different technologies according to the time frame of charging [9]:

- Short term (seconds): capacitors, super-capacitors, flywheel, superconducting magnetic storage (SMES).
- Medium term (minutes): fuel cells, batteries.
- Long term (hours): pumped hydroelectric storage (PHS), compressed air energy storage (CAES).

In the next tables, principal characteristics of different storage technologies have been reported, and the acronyms' meaning has been explained below:

- *ED (Energy Density)*: quantity of energy stored per unit volume;
- *SE (Specific Energy)*: quantity of energy stored per unit mass;
- *PD (Power Density)*: power available per unit volume;
- *SP (Specific Power)*: power available per unit mass.

ES Technology	ED (Wh/l)	SE (Wh/kg)	PD (W/l)	SP (W/kg)	Power Rating	Capital Cost $/kW	Capital Cost $/kWh
Mechanical ES							
PHS	0.5-1.5	0.5-1.5	-	-	100-5000 MW	600-2000	5-100
CAES	3-6	30-60	0.5-2.0	-	5-300 MW	400-800	2-50
Flywheel	-	10-30	-	400-1500	0-250 kW	250-300	500-1000
Batteries							
Pb-acid	50-80	30-50	10-400	75-300	0-20 MW	200-300	120-150
Ni-Cd	60-150	50-75	-	150-300	0-40 MW	500-1500	800-1500
NaS	150-250	150-240	-	150-230	50 kW -8 MW	1000-3000	300-500
Li-ion	200-250	75-200	-	150-315	0-100 kW	1200-4000	300-1300
VRFB	16-33	10-33	-	-	30 kW-3 MW	600-1500	150-1000
Electromagnetic ES							
Super capacitors	10-30	2.5-15	100'000+	500-5000	0-300 kW	100-300	300-2000
SMES	-	0.5-5	-	500-2000	0.1-10 MW	200-300	1000-10'000
Chemical ES							
Hydrogen FC	500-3000	800-10'000	500+	500+	0-50 MW	-	6000-20,000

Table 2.1: Comparison of different energy storage technologies [10]

ES Technology	Response Time	Discharge Time	Storage Duration	Self Discharge per day	Life Time (Years)	Cycle Life (cycles)	Round Trip Efficiency
Mechanical ES							
PHS	1-2 min	1-24 h+	hrs-mos	very small	40-60	-	65-87 %
CAES	1-2 min	1-24 h+	hrs-mos	small	20-40	-	50-89 %
Flywheel	1-2 min	ms-15 min	Sec-mins	100%	15	-	85-95 %
Batteries							
Pb-acid	Seconds	Secs-hrs	mins-days	0.1-0.3 %	5-15	500-1000	75-80 %
Ni-Cd	Seconds	Secs-hrs	mins-days	0.2-0.6 %	10-20	2000-2500	85-90 %
NaS	Seconds	Secs-hrs	Secs-hrs	20 %	10-15	2500	80-90 %
Li-ion	Seconds	Mins-hrs	mins-days	0.1-0.3 %	5-15	1000-10,000+	85-90 %
VRFB	Seconds	Secs-10 h	hrs-mos	small	5-10	12,000+	85-90 %
Electromagnetic ES							
Super capacitors	Millisecs	ms-60 min	Secs-hrs	20-40 %	20+	100,000	90-95 %
SMES	Millisecs	ms-secs	mins-hrs	10-15 %	20+	100,000	95-98 %
Chemical ES							
Hydrogen FC	10 min	Secs-24h+	hrs-mos	Negligible	5-15	100+	20-50 %

Table 2.2: Comparison of different energy storage technologies [10]

Let us go into more detail about some parameters. The round-trip efficiency is the ratio of the electricity output to electricity input. So, it is useful to understand how much electricity will be available during discharging compared to electricity used during charging. Another property useful to analyse losses during the process is the self-discharge per day, which shows the amount of energy lost during a store phase of one day.

Batteries are widespread in off-grid systems as back-up devices. They are mature, reliable and flexible technologies, but there are some issues regarding their cycle life and depth discharge. In fact, a depth discharge of a battery could reduce its life drastically. Flywheels are suitable for regenerative braking, voltage support, transportation, power quality and UPS applications [9]. During charging, the disk store kinetic energy rotating around its axis and, during discharge, it converts it into electricity. Another mechanical way to store energy is PHS. In these systems, excess of energy is used to pump water from a reservoir to another located in a higher position. On the contrary, during peak hours, water flows from the upper reservoir to the lower passing through a hydro turbine and generating electricity. Particular site's conditions are necessary to have a PHS system. CAES also required particular morphology of the site. It is necessary to have a salt cavern, a rock mine, an aquifer or a depleted gas fields to store it compressed air [9]. Air is compressed using the excess of electricity and, when the load is high, it is possible to use it to burn natural gas and to produce energy through a gas turbine. Hydrogen is a way good to store energy for a long time. It can be produced by water-electrolysis exploiting off-peak electrical energy. Hydrogen is stored into pressurised tank (usually in the gaseous state) and then it is used in a fuel cell to produce electricity. Is also possible to adopt electromagnetic energy storage like super-capacitor and superconducting magnet (SMES). The first technology is suited for high power, short discharge applications [9]; the second one uses the excess of electricity to store it in the form of magnetic energy created by a superconducting coil which must work in very low temperature condition. The issues related to SMES concern the high cost and environmental danger due to the strong magnetic field [9].

The correct operation of the system is ensured by the control system. It is necessary to guarantee a continuous supply for the load demand. Its role is to manage the flows of energy in the system according to the current situation. Whenever surplus energy is available, it is sent to the storage subsystem to store the surplus energy and, if the storage system is fully charged, it is wasted in dump load avoiding overcharging [9]. On the contrary, if the demand exceeds generation, the energy stored is sent from the storage to the users.

In Figure 2.1, a general schematic of an HRES has been reported. Several options for generation and storage have been shown but, in common plants, only a few of them are installed together, depending on the scope and the geographical location of the system.

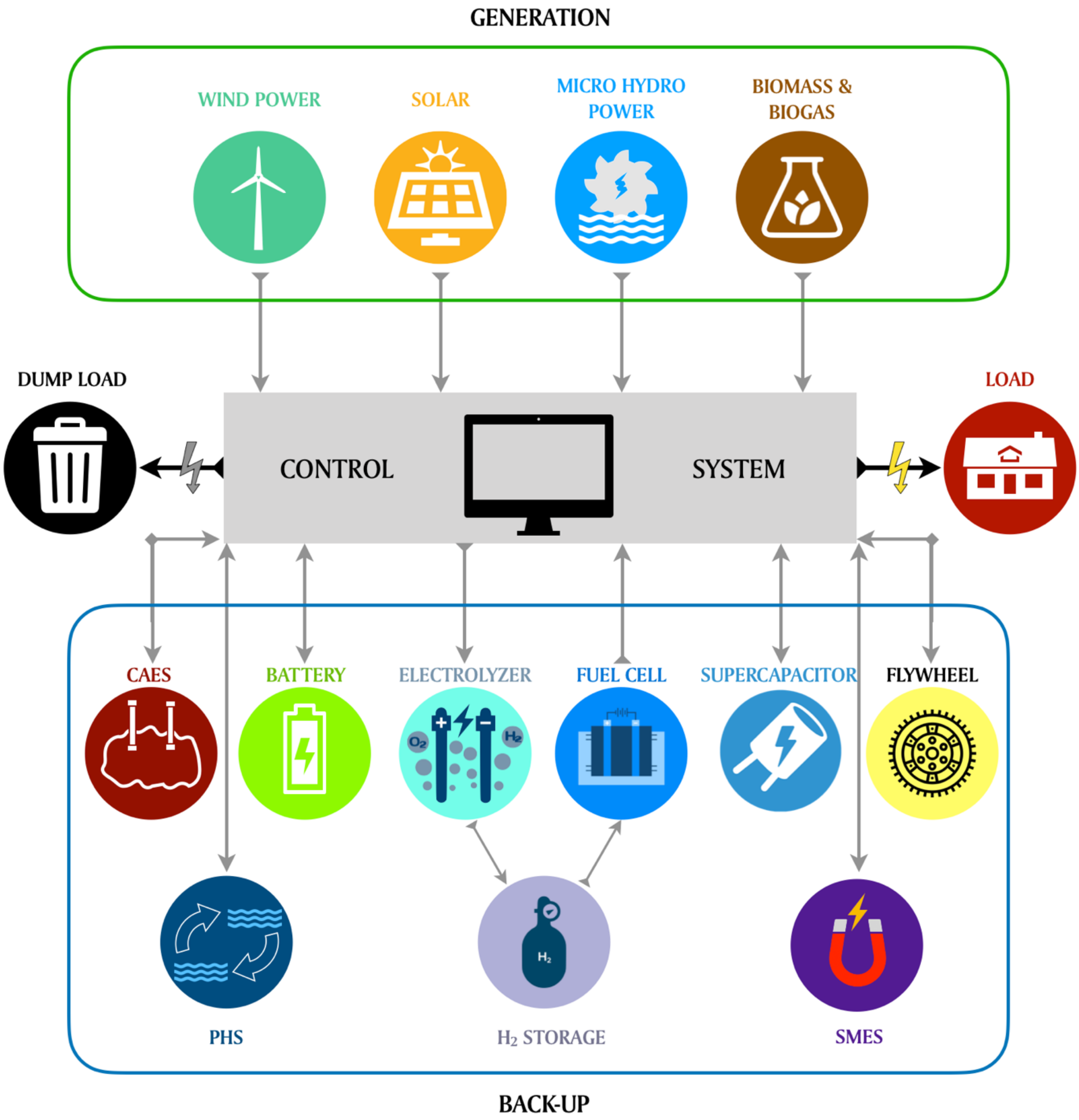

Figure 2.1: HRES general schematic with several alternatives for sources and storages

In particular, we will focus on hybrid systems which utilise hydrogen and batteries together as a back-up. The advantage is the combination of two complementary technologies: as we can see in Table 2.2, hydrogen is good for long-duration storage, but it does not ensure a rapid response in case of necessity. On the contrary, batteries are ready to supply electricity in a few seconds, but they are not suitable for store energy for seasonal storage. In systems using renewable, it is necessary to have long-term storage due to the considerable seasonal variation in power production. It could also be possible to use only battery for this scope, but the life cycle of these devices would not benefit, with a reduction of the expected lifetime. In fact, due to the seasonal variation of the sources, batteries could work at a low state of charge (SOC) with several cycles, and this kind of operation strongly affects the lifetime duration of it [4]. Furthermore, self-discharge for this type of technology is quite relevant, impeding long-duration storage. hese problems can be prevented using hydrogen, and it is also possible to avoid battery's oversizing. Besides, the adoption of this configuration in remote mini-grid could be useful also to provide other services to the community. For example, hydrogen could also be used for transportation, for heat generation (from fuel cell's heat losses or/and combustion in a boiler) and the electricity produced could use by desalination systems, considering that remote place portable water could lack [11] [12].

2.2 Technologies for storage

In a hybrid system based on batteries and hydrogen technologies, the storage can be subdivided into two subsystems: one for the hydrogen storage and one for the battery. For the second one, the battery itself is the main component, while, for the hydrogen, we can distinguish three principal devices: electrolyser, storage tank and fuel cell. Regarding batteries, excess of electricity is converted into chemical energy inside the cell to be converted again in electricity when it is necessary. On the contrary, the process regarding the hydrogen requires more steps and, for this reason, the efficiency is lower. Excess of electricity from renewable is used to convert water into oxygen and hydrogen through water electrolysis inside the electrolyser. So, electrolyser needs a reliable water supply to work and, apart for the hydrogen, it also produces oxygen which could be used for several scopes. After that, hydrogen is stored into a tank where it is usually maintained in the gaseous state at high pressure. It also possible to store hydrogen in the form of liquid or metal hydrates as we can see in the next paragraphs, but these are not the most common choices, especially for stationary application. Finally, during discharging, hydrogen flows towards the fuel cell to generate electricity. Alternativement, some fuel cells can work in reversible mode as an electrolyser, but the efficiency usually decreases because each operation modes requires a fit optimisation. No pollutants are emitted during fuel cell operation, only pure water which can be used by the electrolyser. Batteries do not produce pollutants either during operation, but there are some issues regarding materials utilised, depending on the kind of battery. In the next paragraphs, the operation and the alternatives for electrolyser, H_2 tank, fuel cell and battery have been analysed.

2.2.1 Fuel Cell

Fuel cells generate electricity through an electrochemical reaction. The reactants are outside the cell and, after the reaction, the products produced inside flow outwards. A fuel cell consists of several cells, the unit component, to generate sufficient power for applications. A cell can be subdivided into different elements:

- Anode: where the oxidation occurs. The reaction releases electrons which, passing through a conductor, generate electricity.
- Cathode: where the reduction occurs. Electrons are necessary for the reaction, and they come from the anode passing through a conductor.
- Electrolyte: it is a selective membrane which separates anode and cathode. Only selected ions can pass through, avoiding mixing of anodic and cathodic reactants or electricity losses.
- Interconnector: it is a plate which separates anode and cathode, and it conducts electricity from an electrode to the other one. Furthermore, it must avoid mixing of reactants. Some channels are engraved to allow flow of reactants towards electrodes.

A catalyst is often used to speed up the reaction at the electrodes [13]. A schematic of a fuel cell has been reported below.

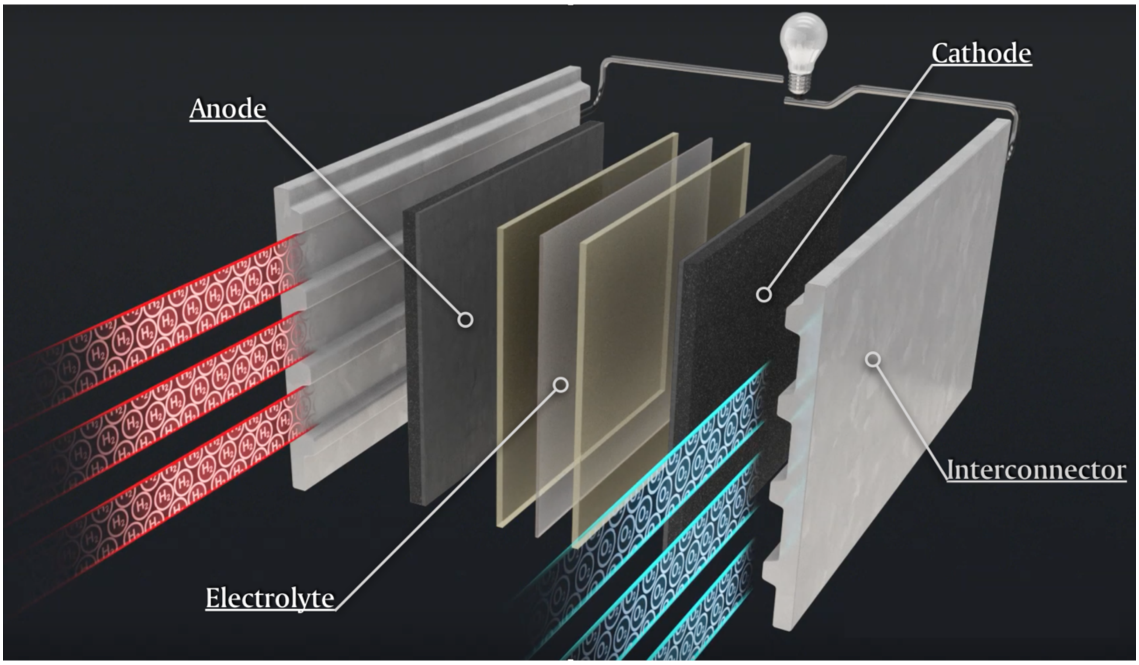

Figure 2.2: Fuel Cell's schematic [14]

Fuel cells are classified primarily by the kind of electrolyte they employ. This classification determines the kind of electrochemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates and the fuel required [15]. In fact, the hydrogen is usually used as fuel, but some kinds of fuel cells can accept other fuel like syngas or natural gas. There are several materials which can be used as electrolyte, both solids and liquids, but all of them must ensure a good ionic conductivity, low electronic conductivity and low permeability to fuel. Instead, electrode materials have to guarantee, at the same time, good properties in ionic, electron and fuel transport. The anode and the cathode can have a different composition, a catalyst and a different design due to the fuels (usually hydrogen for the anode and air or oxygen for the cathode). Interconnector is generally a metal plate with a good electron conductivity. It is necessary to seal all the components together to avoid fuel transit between electrodes. For some application, glass-ceramic sealants are used to stand at high temperature. In **Errore. L'origine riferimento non è stata trovata.**, a comparison between several kinds of fuel cell has been reported.

The power output of the fuel cell derives from the current and the voltage generated by the electrochemical reaction. The electric current depends on the kind of reaction and fuel trough the *charge number* (Z_R) which represents the number of electrons delivered by it from 1 molecule of reactant. The electric current can be expressed from the Faraday law:

$$I = Z_R \cdot F \cdot \dot{n}_R \tag{2.1}$$

Where $F = 96487 \frac{C}{mol}$ is the Faraday constant and $\dot{n}_R$ is the molar flow $\left[\frac{mol}{s}\right]$.

The ideal voltage (or *Open Circuit Voltage*) can be expressed by the Nernst equation as follows:

$$V = -\frac{\Delta g_R}{Z_R \cdot F} + \frac{\bar{R}T}{Z_R \cdot F} \cdot \ln\left(\frac{[Reactants]}{[Products]}\right) \tag{2.2}$$

Where the Δg_R is the Gibbs free energy of the reaction, $\bar{R}$ is the gas constant, T is the temperature and the natural logarithm contains the molar concentration of reactants and products. However, when the circuit is closed, overvoltage losses must be considered:

- Activation overvoltage (η_{ACT}), relating to charge transfer
- Ohmic overvoltage (η_{OHM}), relating to charge conduction, both ionic and electric
- Diffusion overvoltage (η_{DIF}), relating to mass transport

So, the expression of the voltage becomes:

$$V = -\frac{\Delta g_R}{Z_R \cdot F} + \frac{\bar{R}T}{Z_R \cdot F} \cdot \ln\left(\frac{[Reactants]}{[Products]}\right) - \eta_{ACT}(i) - \eta_{OHM}(i) - \eta_{DIF}(i) \tag{2.3}$$

These three contributions, both for cathode and anode side, reduce the available voltage in relation to the value of current density $i\ \left[\frac{A}{cm^2}\right]$ as we can see in …, where the power curve is reported too.

The efficiency is formulated as follows:

$$\eta_{el} = \frac{W_{el}}{(G_{fuel} \cdot LHV)} \tag{2.4}$$

Where W_{el} is the electric power, G_{fuel} is the fuel flow and LHV is the low heating value of the fuel. The efficiency trend is affected by keeping constant the flow in the stack despite the current reduction below a specific value, to avoid starvation issues in the last cells of the stack when the current (and for the proportionality flow too) is low.

Fuel cells also produce heat as a waste of this process, which can be useful for several uses. It depends on a combination of irreversible and reversible phenomena and can be express with the following formula, where $\Delta\bar{h}$ is the molar enthalpy of the reaction $\left[\frac{J}{mol}\right]$:

$$\Phi_{cell} = |\Phi_{REV}| + |\Phi_{IRR}| = \left(-\frac{\Delta\bar{h}}{Z \cdot F} - V_{cell}\right) \cdot I < 0 \tag{2.5}$$

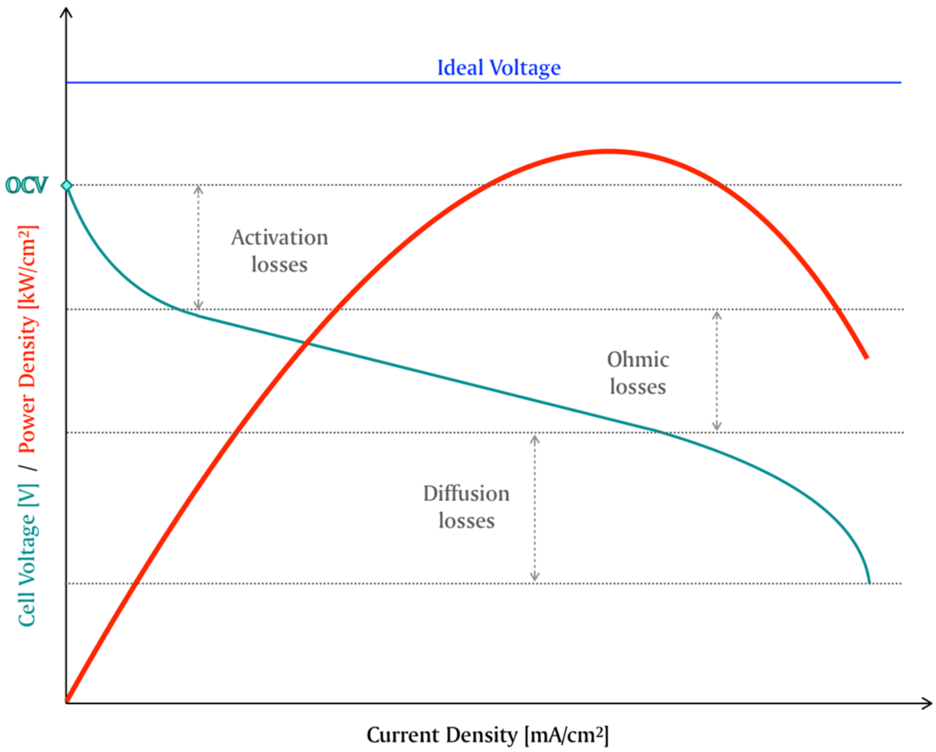

Figure 2.3: typical trend

Fuel Cell type	Advantages	Challenges
SOFC	High efficiency - Fuel flexibility Solid electrolyte - Suitable for CHP Hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components - Long start-up time Limited number of shutdowns
MCFC	High efficiency - Fuel flexibility Suitable for CHP Hybrid/gas turbine cycle	High temperature corrosion and breakdown of cell components Long start-up time Low power density
PAFC	Suitable for CHP Increased tolerance to fuel impurities	Expensive catalysts Long start-up time Sulphur sensitivity
PEMFC	Solid electrolyte reduces corrosion & electrolyte management problems - Low temperature - Quick start-up and load following	Expensive catalysts Sensitive to fuel impurities
AFC	Wider range of stable materials allows lower cost components - Low temperature - Quick start-up	Sensitive to CO2 in fuel and air Electrolyte management (aqueous) Electrolyte conductivity (polymer)

Table 2.3: Advantages and disadvantages of several FCs [16]

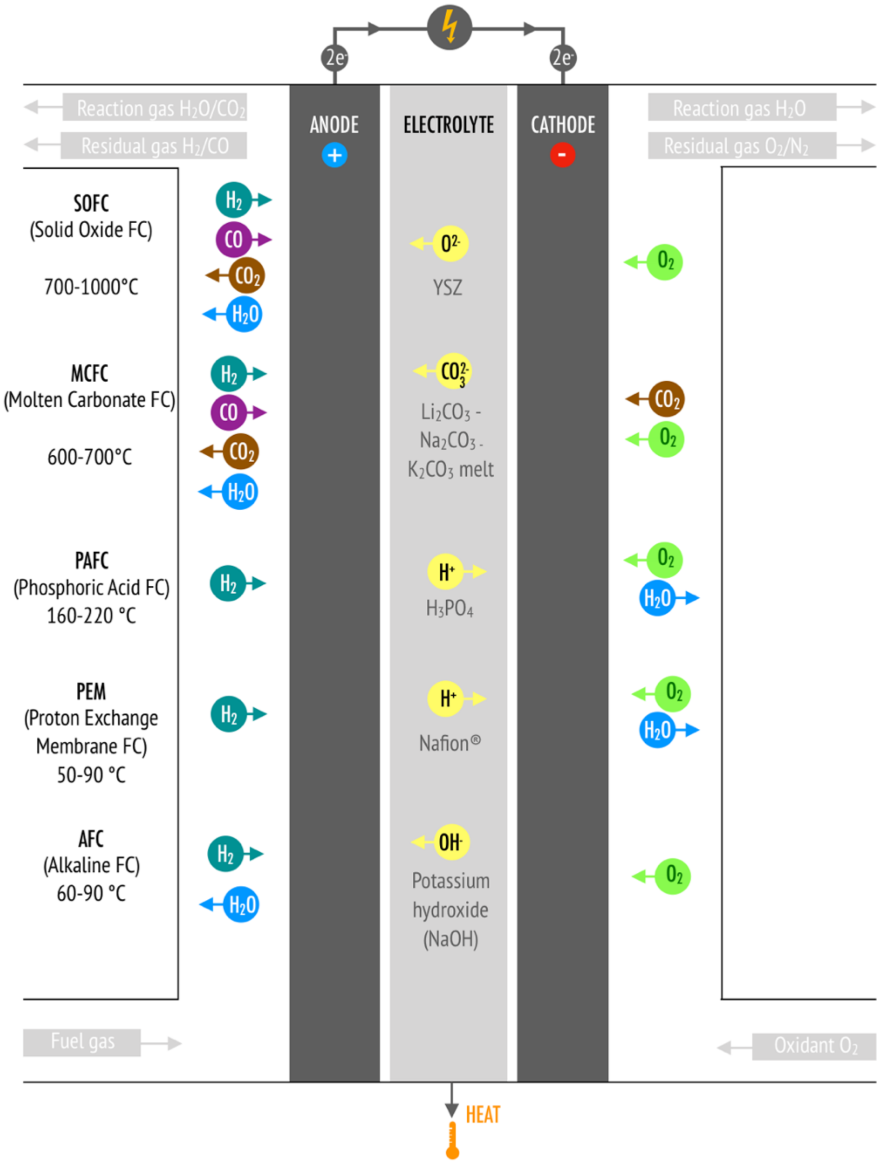

Figure 2.4: Fuel cell schematic of operation and comparison [16] [17]

Fuel Cell type	Fuel	Typical Stack Size	Efficiency
SOFC	H_2, NG, syngas, biogas, methanol (internal reforming)	1 kW – 2 MW	50 - 70 %
MCFC	H_2, NG, syngas, biogas, methanol (internal reforming)	300 kW – 300 MW	55 – 60 %
PAFC	H_2, NG, syngas, biogas, methanol (external reforming)	5 - 400 kW	30 – 40 %
PEMFC	H_2, NG, syngas, biogas, methanol (external reforming)	1 – 100 kW	40 – 60 %
AFC	H_2	1 – 100 kW	50 – 60 %

Table 2.4: Characteristics of several FCs [16] [17]

2.2.2 Electrolyser

Electrolyser operation is the opposite with respect to the fuel cell. Electrolysis is a process using electricity to split water into hydrogen and oxygen. In some electrolyser, carbon dioxide can be used instead of water producing carbon monoxide, a useful molecule for several applications. Structure and operation of the electrolyser is very similar to the fuel cell. An important difference is related to the kind of reactions. In fuel cells, only exothermic reactions are possible, and so a heat release happens. In electrolysers also endothermic reaction can take place. It depends on the technology and the operation mode. As mentioned before for fuel cells, there are two contributions related to heat flow, one reversible and another one irreversible:

$$\Phi_{REV} = \left(\frac{\Delta\bar{h}}{Z_R \cdot F} - \frac{\Delta\bar{g}}{Z_R \cdot F}\right) \cdot I \qquad \Phi_{IRR} = I \cdot \sum_{j=1}^{3} \eta_j \qquad (2.6)(2.7)$$

The reversible term is positive while the irreversible one is negative, so the combination of both depends on the electric current value. For a specific current, the two terms are equal, so the balance between the two is zero. This is the *thermoneutral point* and the corresponding voltage can be calculated from the previous Φ_{cell} equation:

$$V_{TN} = \frac{\Delta\bar{h}}{Z \cdot F} \qquad (2.8)$$

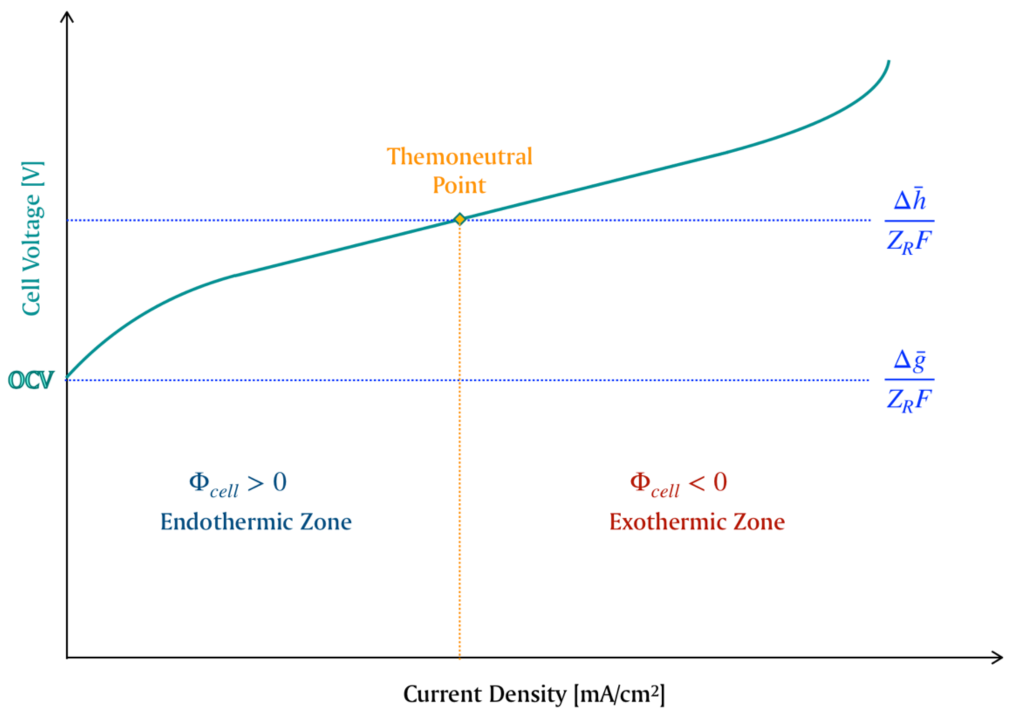

Figure 2.5: Voltage trend and thermoneutral point

In the next table a comparison between different electrolyser technology has been reported.

Fuel Cell type	Temperature	Electrolyte	Plant size	Efficiency
Alkaline Electrolyser (AE)	60-80 °C	Potassium-hydroxide	1.8 - 5300 kW	65 - 82 %
Proton Exchange Membrane Electrolyser (PEM)	60-80 °C	Solid state membrane	0.2 - 1150 kW	65 - 78 %
Anion Exchange Membrane Electrolyser (AEM)	60-80 °C	Polymer membrane	0.7 - 4.5 kW	-
Solid Oxide Electrolyser (SOE)	700-900 °C	Oxide ceramic	-	85 %

Table 2.5: Electrolyser technologies, comparison [17]

2.2.3 Hydrogen tank

Storing large quantity of hydrogen is very difficult due to the low density of this gas at ambient temperature and pressure, around 0.089 g/l, 14 times lighter than air (1.29 g/l) [17]. Due to its lightness, it can also pass through porous materials or inside the metal lattice. For this reason, austenitic steels or coatings using special materials are utilised, to avoid leakage and embrittlement of the tanks [17]. It is necessary to increase the density in order to store hydrogen in restrained volume and to obtain a good energy density. There are two principal methods to do it: physical storage and material based.

Physical storage methods are the most common, especially for stationary application. We can distinguish different kinds of physical storage:

- Compressed gaseous hydrogen (CGH_2): hydrogen is compressed and stored at high pressure, up to 1000 bar. Especially for application which requires very high pressure, composite vessels are used to resist at high strength.
- Liquid Hydrogen (LH_2): hydrogen is liquified at -253 °C (20 K), which is its boiling point at ambient pressure. These methods require a complex and expensive plant to ensure sufficient insulation to the system, so it is usually used for applications which need high levels of purity or for space travels [17].
- Cold and Cryo-compressed Hydrogen (CcH_2): hydrogen is cooled down and then it is compressed. If the final temperature is above 150 K, we obtain cold-compressed hydrogen; otherwise, it is called cryo-compressed hydrogen. This method is suitable for transport application because the energy density is higher than for CGH_2.
- Slush Hydrogen (SH_2): hydrogen is cooled down until the melting point (14 K) when, before it becomes completely solid, hydrogen first changes into a kind of slush or gel with a density 16 % higher than liquid [17].

A comparison between various physical methods is shown in Figure 2.6.

An alternative to physical storage methods is provided by hydrogen storage in solids and liquids and on surfaces. Most of these storage methods are still in development, however.

Moreover, the storage densities that have been achieved are still not adequate, the cost and time involved in charging and discharging hydrogen are too high, and the process costs are too expensive [17]. It is possible to make a classification between several solutions [17]

- Hydride storage systems (or metal hydride): hydrogen is first absorbed on a metal surface and then incorporated forming an interstitial compound with it. Heat is needed to rerelease hydrogen.
- Surface storage systems (sorbents): hydrogen is stored as a sorbate on materials with high specific surface area, like Metal-Organic Frameworks (MOFs), zeolites or carbon nanotubes. Low temperatures are usually necessary for sorption.
- Liquid Organic Hydrogen Carriers (LOHC): hydrogen is absorbed into LOHCs in the presence of a catalyst, temperatures of 150-200 °C and pressures of 30-50 bar. Dehydrogenation requires a heat input around 250-300 °C.

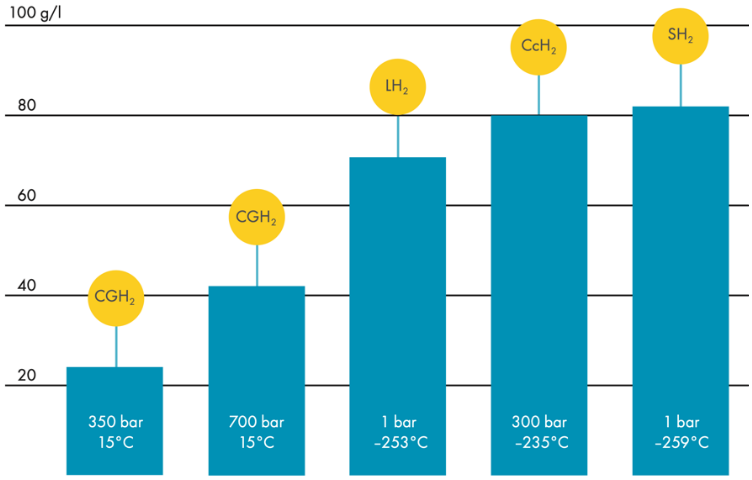

Figure 2.6: hydrogen density of various physical storage [17]

2.2.4 Battery

Batteries consist of two electrodes (anode and cathode) and an electrolyte between but, unlike hydrogen's system, all the reactants are inside the cell and there, are no inward or outward mass flows. Furthermore, electrodes usually actively participate in the reaction and, they change themselves chemical composition (but it depends on the kind of technology). For applications in remote systems, secondary or rechargeable batteries are considered. During discharging, a spontaneous reaction happens, and an electric current is generated. On the contrary, during charging, electric current is supplied, and the opposite reaction occurs, bringing back the cell to the initial condition. Lead-acid batteries are the most mature technologies among secondary batteries used as storage systems [18]. They are largely used in stand-alone systems thanks to low price, good reliability and low self-discharge. However, they have a short life, low energy density, issues regarding gases release and toxicity of lead [10]. For these reasons, several alternatives have been investigated, like Nickel-cadmium (NiCd), Sodium-sulphur (NaS) or Lithium-ion (Li-ion) batteries. Although NiCd batteries have higher efficiency and a better life duration than lead-acid, they are unsuitable for remote applications based on variable renewable sources due to the memory effect [10]. This phenomenon happens if NiCd batteries are repeatedly recharged after being only partially discharged, and it causes a gradual reduction of the maximum energy capacity. Moreover, cadmium is toxic and dangerous for health and the environment. NaS batteries also have better features compared to lead-acid, like a higher power density, a better efficiency and a longer life, but they need a heat source to work at high temperature, around 300-350 °C, in order to keep electrodes in molten stage, and this represents an obstacle to diffusion of them [10]. Besides, the interest for Li-ion batteries in stand-alone applications is grown recently. This kind of technology is widespread in portable consumer electronics markets and lately in hybrid and electric vehicle [19]. The possibility to scale up to any size, high energy density, high efficiency, long life cycle and low self-discharge rate are positive features for stand-alone applications, though costs are quite higher in comparison with other technologies [10]. However, around 55% of global battery energy storage system installed capacity in 2016 were based on Li-ion [18].

Alternative kinds of rechargeable batteries are the redox flow batteries. The main difference with the previous technologies is that the electrolyte contains one or more electro-active species flows through an electrochemical cell and additional electrolyte is stored externally, generally in tanks. The electrolyte can flow through the cells using a pump or a gravity field system [19]. The advantage of this system is the possibility to increase the capacity merely expanding the tanks. Tolerance to overcharging, low support cost and capacity to deep charged without influencing the cycle life are other points of interest [10]. We can distinguish two kinds of flow batteries [19]:

- Only dischargeable cells, with irreversible electrochemical reactions, which can be recharge changing the electrolyte, and so they are more properly primary batteries;
- Rechargeable cells, with reversible reactions.

Vanadium redox flow batteries (VRFB) are an example of rechargeable flow batteries. In paragraph 2.1 (Table 2.1 and Table 2.2), several features of the presented technologies have been reported. A schematic of a VRFB is shown in the next figure.

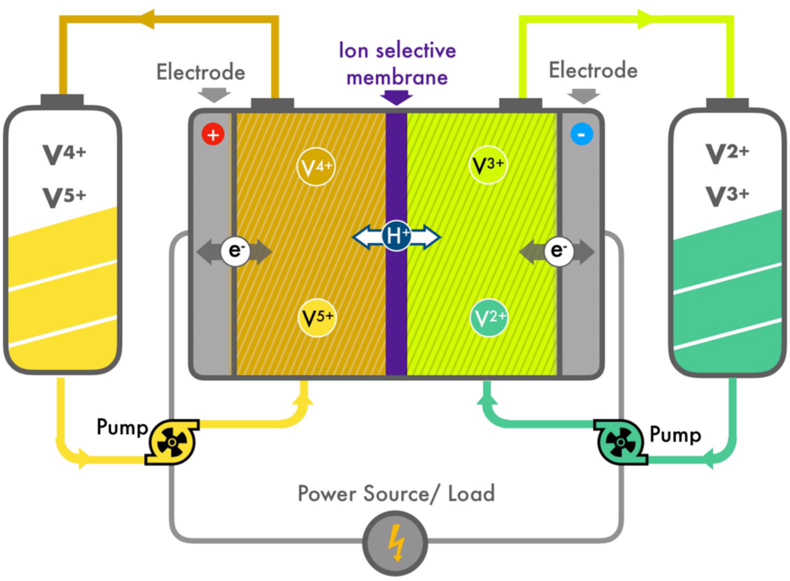

Figure 2.7: VRFB schematic

3. Sizing methodology

Hybrid systems based on renewable and battery-hydrogen back-up required an optimal sizing to satisfy the load and to design an economically sustainable plant. The system must be reliable both from an energetic and economic point of view, so several parameters are used to evaluate that plant can respect certain conditions. It is possible to choose different approaches and methodologies for sizing, like [9]: artificial intelligence approaches (AI), multi-objective design, iterative approach, analytical methods, probabilistic approaches, graphical construction methods. Some commercial computer tools are available on the market, such as HOMER (Hybrid Optimisation Model for Electric Renewables) which is one of the most popular. It compares various design configurations based on their technical and economic merits, but it does not allow the user to select appropriate system components [9].

SINTEF develops its own optimisation model for the sizing of the various demo cases of the *Remote* project. It is called HyOpt and is a techno-economical model, so it helps to find the optimal composition, dimensioning and sizing of the system minimising its NPV (Net Present Value). Once a structure of the energy system plus expected energy demands and costs are provided, the model decides which elements should be included and with what capacity. In addition to the proposed structure, the model also decides (dynamic) operation of the elements and reports investment and operational costs over a specified time horizon [20]. All elements in the modelled system are represented as nodes with some specified properties [20]. For each pair of nodes, we can then allow flows of some products between them. Possible products include hydrogen (compressed or liquid), oxygen, electricity, water, natural gas. The flow can be optionally allowed only in some periods, which allows for modelling of downtime, or availability of transport between two nodes (such as a ship) [20]. Nodes are classified in different categories [20]:

- *Production plants*: these nodes receive a product in input and then they convert it in another one. The output is evaluated as a function of the input, in the simplest case using the efficiency. Example: electrolyser, fuel cell, turbine etc.
- *Markets*: they are nodes with a load or a demand for a product. Supply of loads is mandatory, else there could be a penalty, while that of demands is optional.
- *Storage*: nodes store products between time periods. Example: storage tanks and batteries.
- *Transport*: these nodes are useful to evaluate transmission losses of products between two different nodes or, if necessary, to put a price or to limit the flow.

Some input parameters are necessary to feature the nodes [20]:

- existing capacity (if any);
- maximum allowed capacity;
- CAPEX (fixed and capacity dependent);
- OPEX (fixed and variable);
- production function between input and output products;
- efficiency;

- degradation and maintenance information.

For storage nodes, further specifications can be [20]:

- minimal fill level;
- maximal rate of filling (e.g. m^3/h for hydrogen or capacity per hour for batteries);
- efficiency of filling and emptying.

The simulation develops into more strategic periods, typically on year or longer. Inside each strategic period, there is a sequence of operational periods (weeks, days, etc.) [20]. Every investment or change in the system is placed at the beginning of a strategic period.

The HyOpt model includes two kinds of variables, strategic and operational. Strategic variables are for decisions done at the beginning of the strategic periods, and they regard the choice to add or remove capacity from a node [20]. Instead, operational variables are used for all decisions in the operational periods like [20]:

- production at production nodes;
- loads delivered to, or obtained from, the market nodes;
- storage levels at the storage nodes;
- flows between nodes;

It is also possible to insert technical and policy constraints. The purpose of the model is to determine the optimal design of the plant, so it chooses which nodes should be installed and their appropriate capacity. This choice is based on the solution of an objective function, that is typically the minimisation of the NPV as a balance between revenues and costs, with a given discount rate [20]. The discount rate represents the rate of return used to discount future cash flows back to their present value [21]. It is usually chosen equal to the Weighted Average Cost of Capital (WACC) and it should include, among the others, the inflation during the whole lifetime of the project. Currently, in the model, the real discount rate (d) considering inflation is equal to 0.049, but two more correct parameters are used in the evaluation of the NPV [20]. The first one is the discount rate applied at the beginning of the strategic period:

$$Dis_{st} = D_y^{(i-1)\cdot t} \tag{3.1}$$

Where:

- t is the duration of the strategic periods (e.g. 10 years);
- i represents the strategic period;
- $D_y = \frac{1}{1+d}$ is the yearly discount factor.

The second one is the discount rate applied in the middle of the strategic period:

$$Dis_{av} = \frac{D_y^{(i-1)\cdot t} - D_y^{i\cdot t}}{\frac{\ln(1+t)}{t}} \tag{3.2}$$

So, the NPV is calculated with the following formula:

$$NPV = \sum_{i=1}^{sp} \left[-Dis_{av} \sum_{a=1}^{t} Income_{a,i} + Dis_{st} \cdot CAPEX_i + Dis_{av} \sum_{a=1}^{t} OPEX_{a,i} + \sum_{a=1}^{t} \frac{RC_{a,i}}{(1+d)^{a+(i-1)t}} \right] \quad (3.3)$$

Where:

- sp : strategic period (currently the model considers 2 strategic periods);
- $Income_{a,i}$: revenues in year a of the strategic period i;
- $CAPEX_i$: capital expenditures (including transport and installation costs) due to investments in the system in the strategic period i;
- $OPEX_{a,i}$: operational and maintenance costs of the system in year a of the strategic period i;
- $RC_{a,i}$: regeneration cost due to periodic reinvestment/regeneration needs to maintain the operation of the system, applied at the end of the year a of the strategic period i.

In the next figure, an example representing the logics of the HyOpt model has been reported.

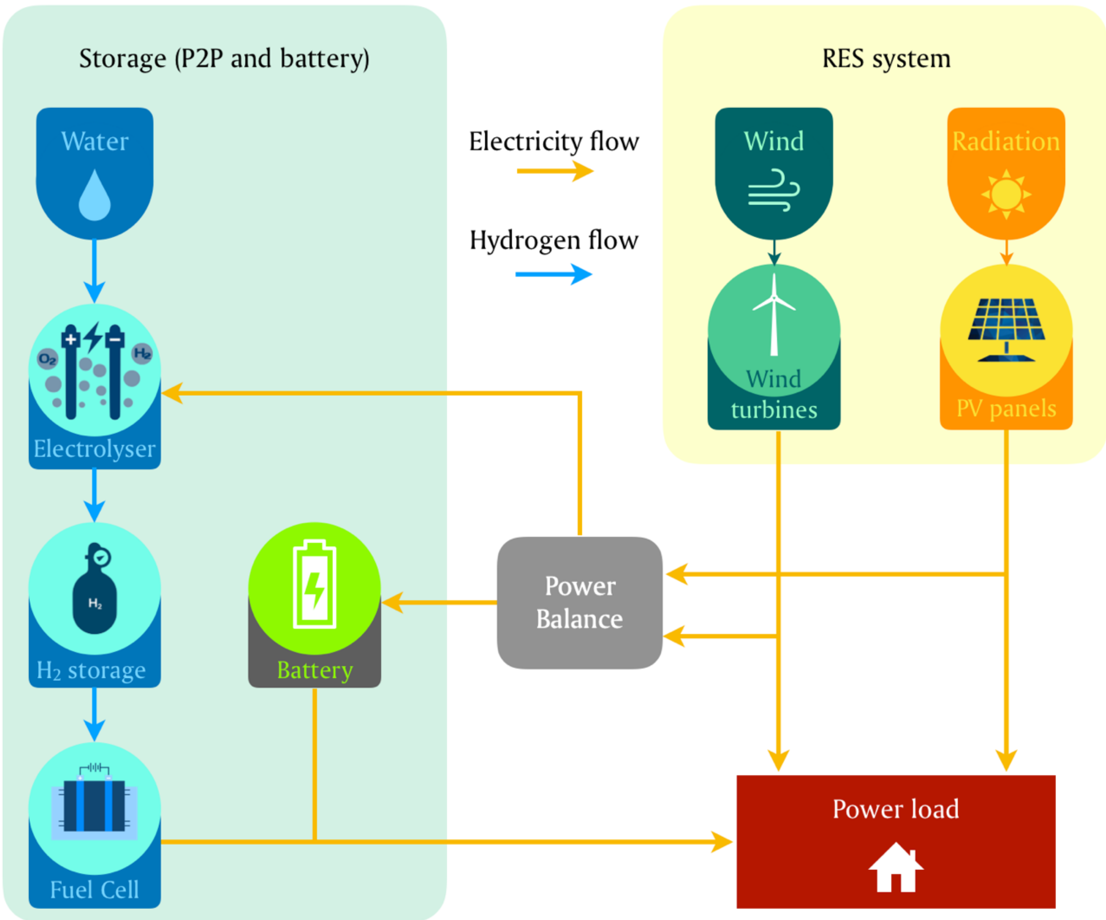

Figure 3.1: Example of energy generation and storage system analysed with the HyOpt optimisation model

4. Realisation of the Excel tool

4.1 Structure of the model

HyOpt consists of three parts: an Excel front end, an SQLite database, and the optimisation model itself, written in the FICO™ Mosel optimisation language. The typical workflow starts by specifying the input in the Excel front end. This includes the list of the proposed network elements and their properties, the time structure and all required time series. Then one runs Mosel, which reads the input data from Excel or the database, constructs an optimisation-model instance, solves it using the FICO™ Xpress solver, and then pushes the results back to the Excel file and the database. Thereafter, one can study the results in several automatically generated tables and charts. The model manages several data as input to obtain an optimisation of the system. However, in this work, a simplification of the interface has been done. Users can introduce relatively few input information about technologies, meteorological data and electrical load and results are reported in some excel sheets showing economic and operational data.

Next figure shows a scheme of the model reporting all its parts and their interactions. In the picture, a resume of the new Excel tool configuration is also present, with its new input and output sheets. The operation and description of these sheets have been explained in the following paragraphs, illustrating the various components they contain. Current input and output requirements of the model will be explained to understand the starting point of the tool realisation thoroughly. Furthermore, the appendix reports the screenshots of all the new sheets.

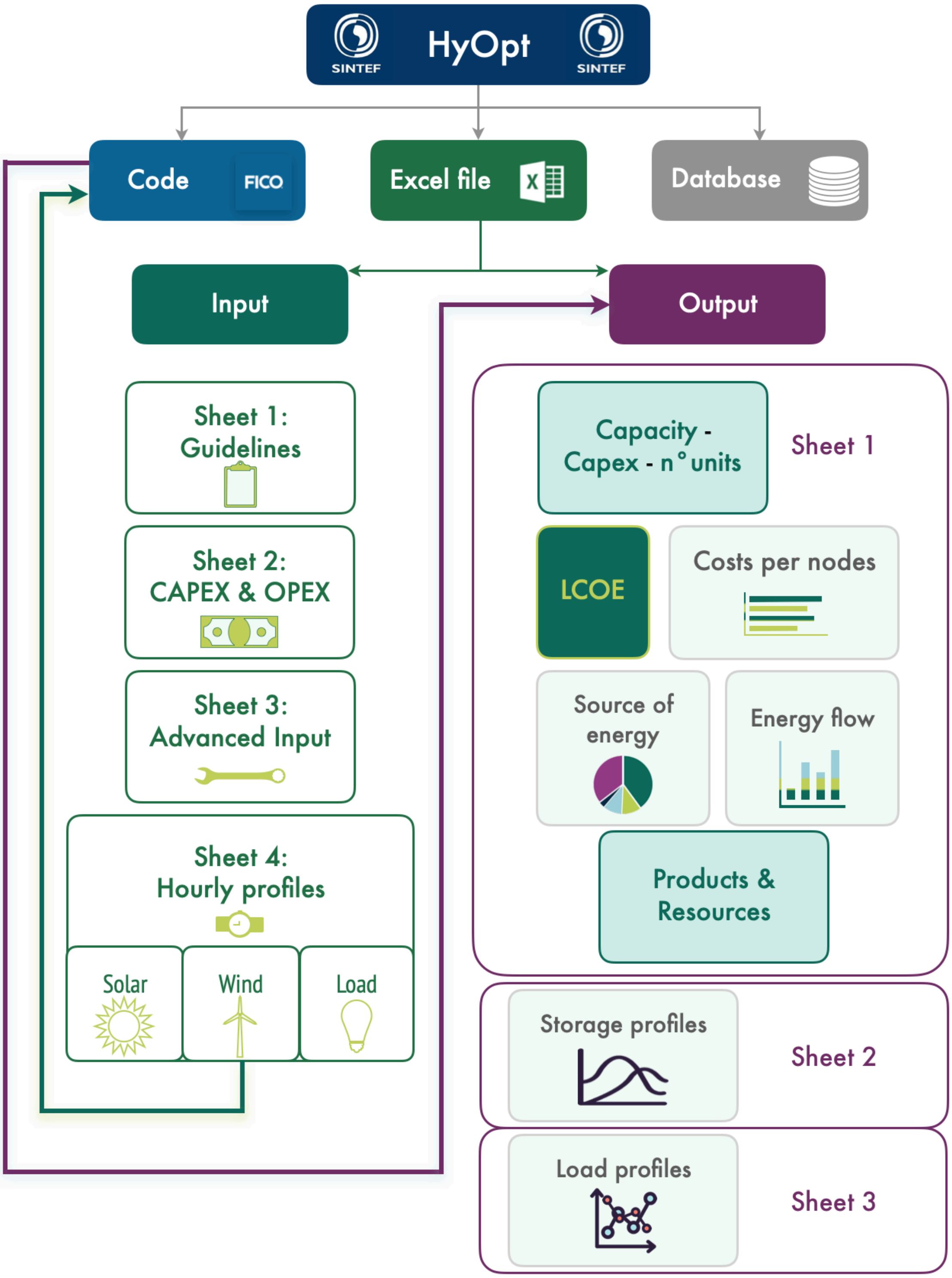

Figure 4.1: Scheme of the model

4.2 Input data

The HyOpt model requires many input data that are reported in the original excel file. Meteorological data are specific of the different Demo's sites, instead many of technological data are supplied by providers, so they cannot be released. Input can be distinguished in several categories. First of all, it is necessary to insert general information about the plant. For each node, the following data are inserted in the model:

- Reference unit (MW, MWh, kg etc.)
- Existing capacity: possible capacity, which is already present, can be added here. It is also possible to decide about extension or not of eventual existing capacity.
- Constraints about capacity (maximum, minimum, block size).
- CAPEX.
- OPEX.
- Power consumption (usually referred to the reference unit).
- Capacity loss per year.
- Lifetime.
- Average capacity utilization.
- Removal cost and rest value.

Only some of these are indispensable for the functioning of the model. Moreover, it is possible to include or exclude some nodes at its own discretion. Nodes are usually physical components of the plant (fuel cell, battery, wind turbine etc.) but, in some case, they represent markets, the power balance or the power load, so previous features lose meaning and the only things to do is to include them or not.

Then, it is possible to add further information about the storages (battery and hydrogen tank). These specifications can regard:

- Initial fill
- Buffer level
- Maximum and minimum rate of empty speed
- Efficiency (for batteries)

Next input typology regards the market. Here it is possible to distinguish between demands or supplies which, as it was written in the previous paragraph, are optional, and loads, which must be satisfied. For the latter, the cost of unsatisfied load and the percentage of required regularity can be specified. Other specifications can also be inserted in one of the following sheets, including several constant market data:

- Load price (per MWh)
- Possibly demand price of hydrogen, power or other from markets
- Supply price of necessary sources for the system (water, diesel fuel, gas etc.)
- Grid tariff, in the case of a grid connection
- Power tariff

Further input about technologies can be inserted specifying eventual slack cost of products and maintenance cost.

In the second sheet of the excel file, there is a table reporting information about production functions. For each plant, the following inputs are necessary:

- Product (hydrogen, power, heat or other substances)
- Reference unit of the source
- Reference unit of the product
- Value of the ratio between products and sources or, where appropriate, advanced production function

In another table, it is possible to activate links between nodes, defining products exchanged by them.

Next step regards meteorological data to define power production from renewable sources. For the Remote project, all data are available following experimental surveys on the Demo sites. These surveys produced data about wind speed [m/s] and solar irradiance [W/m^2]. For Agkistro sites, past data from existing hydroelectric plant has been used. The power production has been estimated starting from these data. All information is reported with hourly precision for an entire year (8760 hours). The typical power load, required by the system, also has to be provided for each hour of an entire year.

Eventually, the model requires time specification. In the excel file, users must define number and duration (in hours) of the strategic periods. Then, for each strategic period, operational periods must be added, specifying their duration (e.g. one hour).

The explained setup of the excel file allows inserting a wide variety of data, ensuring an accurate description of the case to analyse and a vast possibility of customisation. However, the Sintef's aim is to make accessible this tool to expert users that want to explore the possibility to realise a system based on renewable and hydrogen and battery; in this formulation, the excel file could be too complex to use without a good knowledge of it. For this reason, with this work, we tried to create a smart and essential configuration of the input part of the model. It was thought to add some new sheets in the excel file. So, the users can download the code and the Excel files, and then they can insert their input data and run the code. After that, the results report will appear in the same Excel file but in other sheets (as we can see in the next paragraph).

4.2.1 New input sheets

The design of the new sheets for input is more straightforward than the previous, and it allows us to insert only the essential data.

The first sheet (name: "Guidelines") contains information about the code and several guidelines to allow users a correct utilisation. As we can see in the appendix (Figure 8.1), there are also some explanations about the outputs which will be treated in the following paragraph. In addition, two websites are suggested to allow users to obtain data about irradiance and wind. These directions can be useful to those who do not have available data about them from their sites.

The second sheet (name: "Economic input") contains several tables regarding the principal nodes of the system:

- Battery
- Electrolyser
- Fuel cell
- Compressed H_2 storage
- Hydrogen compressor
- Wind turbine
- Photovoltaics panels
- Diesel generator

Each table can be included or not digiting respectively "1" or "0" on the top of the table, alongside the cell "Include". This operation allows the user to insert or not a specific system in his analysis. All the component of the hydrogen system (electrolyser, fuel cell, compressor, storage) are inserted in the same table with the possibility to select just the entire system since the selection of one without the others would not make sense. The colour of the cell with the number (1 or 0) appears green, thanks to the conditional formatting, to underline the inclusion of the nodes, otherwise it appears red. Some explanations have been added as we can see in the next figure.

Include	1						
Node				**CAPEX Fixed**	**Unit**	**CAPEX variable**	**Unit**
	Lead-Acid	Flooded LA			€	139,7	€/kWh
	Lead-Acid	VRLA			€	249,9	€/kWh

Include	0						
	Node			**CAPEX Fixed**	**Unit**	**CAPEX variable**	**Unit**
BACK-UP	Diesel generator	Diesel generator			€	552,5	€/kW
GENERATOR	Insert your data	New			€		€/kW

Figure 4.2: detail of the "include" cell in two different case

First of all, in the first column of each table, we can find the name of the node, or of the system in the case of hydrogen. The following two columns contain further information about the typology of the technologies. For example, regarding batteries, different typologies have been considered, distinguishing between lead-acid, lithium-ion and flow batteries, and for each of them a further distinction has been made. Other columns are intended for CAPEX and OPEX data. The user can choose, through a drop-down menu in the bottom row of the table, between several data reported in the table and extracted from market analysis. Otherwise, it can insert their own data in the penultimate line and then can select it from the drop-down menu under heading "New".

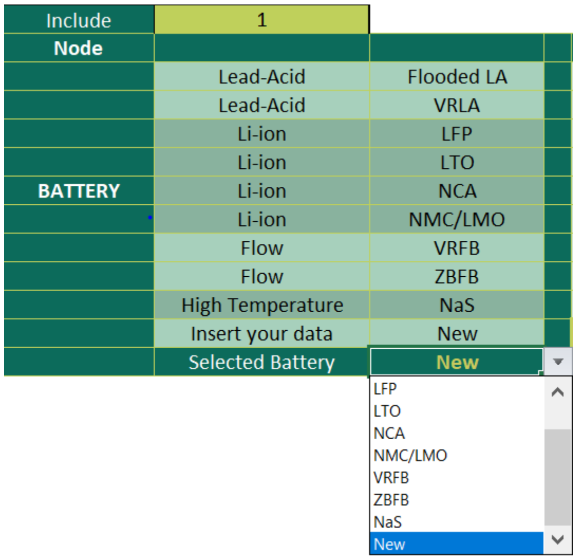

Figure 4.3: drop-down menu of the battery table

CAPEX can be defined in several ways. We can distinguish fixed CAPEX [€], which are usually not available from database data present in the table, but they can be added by the users, or variable CAPEX, which are usually expressed as a function of the reference unit. For OPEX we can also distinguish between fixed and variable but with some clarifications:

- Fixed OPEX, as a percentage of the CAPEX
- Fixed OPEX, as a function of the reference unit
- Fixed OPEX [€]

All OPEX shown in the table are referred to one year. CAPEX and OPEX have been obtained from different documents, where the data are presented in currencies and referred to different years (between 2016 and 2019). All the values have been reported in € (or cents of €) and discounted at December 2019. Exchange rates used are reported in the next table. In the following tables (Table 4.2 - Table 4.9), we can see original and discounted CAPEX and OPEX for each node.

Currencies	2016-2019	2017-2019	2018-2019	2019-2019
NOK-EUR	0.108	0.113	0.104	0.099
USD-EUR	0.95	0.97	0.85	0.90
EUR-EUR	1.04	1.03	1.02	1

Table 4.1: exchange rates [22]

Battery

Typology	Model	CAPEX [$/kWh]	CAPEX [€/kWh]	OPEX [% of CAPEX]	Round trip Efficiency [%]
Lead Acid	Flooded LA	147	139.7	4 %	82 %
Lead Acid	VRLA	263	249.9	4 %	80 %
Li-ion	LFP	578	549.1	4 %	90 %
Li-ion	LTO	1050	997.5	4 %	96 %
Li-ion	NCA	352	334.4	4 %	95 %
Li-ion	NMC/LMO	420	399.0	4 %	95 %

Table 4.2: CAPEX and OPEX for batteries [23] [24] [25]

Electrolyser

Typology	CAPEX [€/kW 2017]	CAPEX [€/kW 2019]	OPEX [% of CAPEX]
Alkaline	750	766	3 %
PEM	1200	1226	3 %

Table 4.3: CAPEX and OPEX for electrolysers [26] [27]

Fuel cell

Typology	CAPEX [€/kW 2017]	CAPEX [€/kW 2019]	OPEX [% of CAPEX]
Fuel Cell	5000	5109	5 %

Table 4.4: CAPEX and OPEX for fuel cells [26] [28]

Storage

Typology	CAPEX [€/kg 2017]	CAPEX [€/kg 2019]
Compressed H_2	400	409

Table 4.5: CAPEX for hydrogen storage [26]

Hydrogen Compressor

Typology	CAPEX [MNOK/kg/h]	CAPEX [€/kg/h]	OPEX [% of CAPEX]
Compressor	0.2	19724	4 %

Table 4.6: CAPEX and OPEX for hydrogen compressor [29]

Wind Turbine

Typology	CAPEX [$/kW]	CAPEX [€/kW]	OPEX [$/kW]	OPEX [€/kW]
Onshore	1498	1273	44	42,7
Offshore	4353	3700	144	139,7

Table 4.7: CAPEX and OPEX for WT [30] [31]

Photovoltaic panel

Typology	CAPEX [$/kW]	CAPEX [€/kW]	OPEX [$/kW]	OPEX [€/kW]
Rooftop residential	2875	2587	19.5	17.55
Rooftop C&I	2350	2115	17.5	15.75
Community	1950	1755	14	12.6
Utility scale	1000	900	10.5	9.45

Table 4.8: CAPEX and OPEX for PV panels [32]

Diesel generator

Typology	CAPEX [$/kW]	CAPEX [€/kW]	OPEX fixed [$/kW]	OPEX fixed [€/kW]
Generator	650	630.5	10	9.7

Table 4.9: CAPEX and OPEX for diesel generator [33]

For each node, at most one kind of CAPEX, fixed OPEX and variable OPEX is present in the table. If users decide to insert their own data, it is mandatory to insert at least one value for CAPEX and one for OPEX, but they cannot put more than one value for CAPEX, one for fixed OPEX and one for variable OPEX. Furthermore, it is necessary not to change reference units and to use the same as the database. The sheet aspect and its tables have been shown in the appendix (Figure 8.2).

Unlike other nodes, battery's table has got one more column where there are round-trip efficiency values. Users can enter their value in the penultimate row if they decide to insert personal data about their own battery. However, an average value has been added to avoid leaving that cell empty in case the user has no data to put there.

Regarding solar photovoltaic panels, different plant sizes have been reported in the corresponding table. For each, the maximum capacity of the plant is indicated in an additional column of the table. These values are just indicative, and they will not be considered by the code, so users have not to respect it for mandatory. If users want to fix a maximum capacity, they can do that in the third sheet, as we will see below.

In the table for the back-up diesel generator, an additional column is also present, indented for fuel price. The diesel fuel price is already reported (relating to the price in Norway on 3rd December), but users can modify it with an updated value or the price of a different fuel used. The price is indicated in €/kg to allow users to enter also data of fuel with different density.

In the last row of each table, we can see the selected data. These cells are linked with the following pages, where we can find the pre-existent structure as it has been explained before. Eventually, the model can read these values from here and process the result.

The third sheet (name: "Advanced input") allows adding advanced information about the previous nodes. It is not mandatory to use this sheet because data contained in the second sheet are sufficient to run the code. However, users can decide to add additional information here to have a finer analysis or to express some peculiar requirements.

In this sheet, we can find a table with information about each node. For every node, three rows are present. The first one contains standard information, namely information which will be considered by the code if the user will not decide to modify them. The second row is reserved for users to add their data. The last one, like in the tables of the previous sheet, allow to select between "Standard" and "New", and it prints the choice. Moreover, it is possible to subdivide the table into three blocks per each node. The choice ("Standard" or "New") is valid for all the cells in the block. For example, if a block contains "Specification 1" and "Specification 2" and the user decides to use information from "Standard" row, both "Specification 1" and "Specification 2" will be taken from "Standard". The three blocks are about:

- Existing capacity: users can decide to introduce information about the already present capacity of a system if they select "New". Otherwise ("Standard"), code will assume no existing capacity for that node
- Binary investment: if users select "New" and add information about "Capacity block size", "Minimum capacity" and "Maximum capacity", a binary investment for that node will be considered. In this case, the code must consider capacities that are multiples of the block size and that are within the thresholds. Otherwise ("Standard"), these constraints do not have to be respected by the code because the investment is not binary.
- Buffer level: this block is reserved for battery and hydrogen storage. It represents the minimum level to respect. Users can add their own values ("New") or leave that from libraries ("Standard"). The standard value changes according to the selection of the battery in the previous sheet.

In the appendix, Figure 8.3 shows the configuration of this table.

The fourth sheet (name: "Profiles") of the Excel file allows to user to add its own data about renewable sources and load profiles. There are three tables, indented for wind, solar and load data. The model requires hourly data for a whole year, so, for each table, we can find 8760 rows in which it is possible to insert data. In the first column of each table, the indication of the hour has been reported. We can assume that the hour "1" represents the first hour of the first day of the year. However, this is not strictly necessary, and the user can decide to insert data starting from whatever hour of the year, provided the data are ordered and consistent in each of the three tables.

The first table is reserved for wind data. The code requires the production rate hour by hour. Users can simply enter the wind speed data in the specific column, and the file will automatically calculate the production rate in the following column. The calculation is done considering the thresholds in the part of the table regarding the production function. Below "Cut-in" and above "Cut-off", the power production is zero; between "Rated" and "Cut-off", the power production is equal to the rated value; between "Cut-in" and "Rated", the power follows a linear pattern from zero to rated value. The user can change these values and can also vary the trend of the power between "Cut-in" and "Rated" changing the order of the curve (the current value is 1 because we assume it is linear). Users can also directly insert the production rate hour by hour in the third column.

In the second table, users can add hourly data about solar irradiance in W/m^2. The code will calculate the power production automatically starting from that.

Eventually, in the last table, it is possible to add the load of the users, using MW as reference unit. As for previous sheet input, these values are connected to the following sheets to be read by the code.

The configuration of these sheets is shown in the appendix (Figure 8.4) reporting only some rows.

4.3 Output data

After running the model, it produces several results and displays it in some tables of the Excel files. In particular, the original Excel file contemplated five sheets for results more one as an overview.

The first sheet is for the economic results. There is a table where we could find several values for each node:

- Installed capacity
- Total capacity
- Total cost
- CAPEX
- Fixed and relative OPEX
- Supply cost
- Demand and load income
- Value of the lost load and other costs

Of course, if some optional input data was not supplied, some of these columns will not display any values.

The second sheet shows the production results and the flows from one node to another. In the first two columns, the flow of water, power and hydrogen inward and outward the nodes have been shown. Then we can find information about slacks or emissions (heat, water, power) and about power losses. The last table reports the balance of these flows.

The third and the fourth sheets display, respectively, storage profiles and load profiles. These charts will be discussed more thoroughly afterwards because they have been used, practically without changes, in the new sheets introduced for users.

The fifth sheet contains data shown in the previous sheets, hourly data (for flows, storage levels, etc.), yearly data and economic parameters which have been used in the model.

4.3.1 New output sheets

Three new sheets have been added to guarantee easier and faster reading of the results, and, as it has been done for input, the old sheets have been hidden. The new sheets contain charts and tables which show the most relevant economic results, flows of products and simulations of the system operation for the whole year.

The first sheet (name: "User Results") contains various information about costs and flows. On the top of the page, we can find a resume of the characteristics of the most important nodes. For each node there is a panel containing the following data:

- Capacity (kW except for battery in kWh and hydrogen storage in kg)
- Number of units (only if the unit capacity has been defined in the input)
- Price, referred to the CAPEX (in thousands of €)

An example is shown in Figure 4.4.

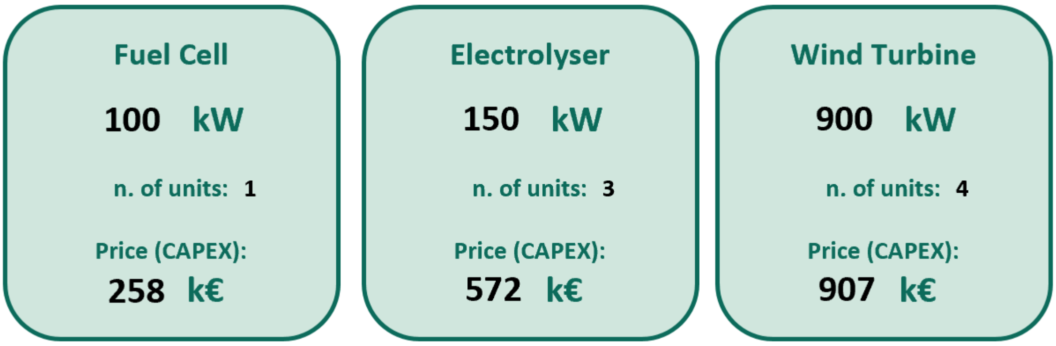

Figure 4.4: Main characteristics of some systems

In addition to this information, the cost of electricity produced is another important parameter to evaluate the investment and to compare it with alternative solutions. So, the following panel reports the Levelized Cost of Electricity (LCOE). This value has been calculated as follows:

$$LCOE = \frac{\sum_{i=1}^{sp}\left[Dis_{st} \cdot CAPEX_i + Dis_{av}\sum_{a=1}^{t} OPEX_{a,i} + \sum_{a=1}^{t}\left(\frac{RC_{a,i}}{(1+d)^{a+(i-1)t}}\right)\right]}{Yearly\ energy\ delivery \cdot \frac{1-(1+d)^{-sp\cdot t}}{d}} \tag{4.1}$$

The numerator is composed by the sum, per each strategic period, of three elements. The first one is the total CAPEX in the strategic period. This value is discounted using the discounting value (Dis_{st}) at the beginning of the strategic period. The second element is the sum of OPEX in each year of the strategic period and then discounted using the average value (Dis_{av}) in this period. The last one is the sum of the regeneration cost at the end of the year a of the strategic period i ($RC_{a,i}$), in each year of the strategic period analysed, dived by a factor containing the real discount rate considering inflation (d). The denominator is composed of the $Yearly\ energy\ delivery$ multiplied by a parameter containing the real discount rate.

Figure 4.5: LCOE's panel

Further economic information is contained in the next charts. Here, we can find a comparison of the cost related at each node throughout the entire lifetime of the plant, distinguishing between CAPEX and OPEX. Costs are expressed in thousands of Euros (k€).

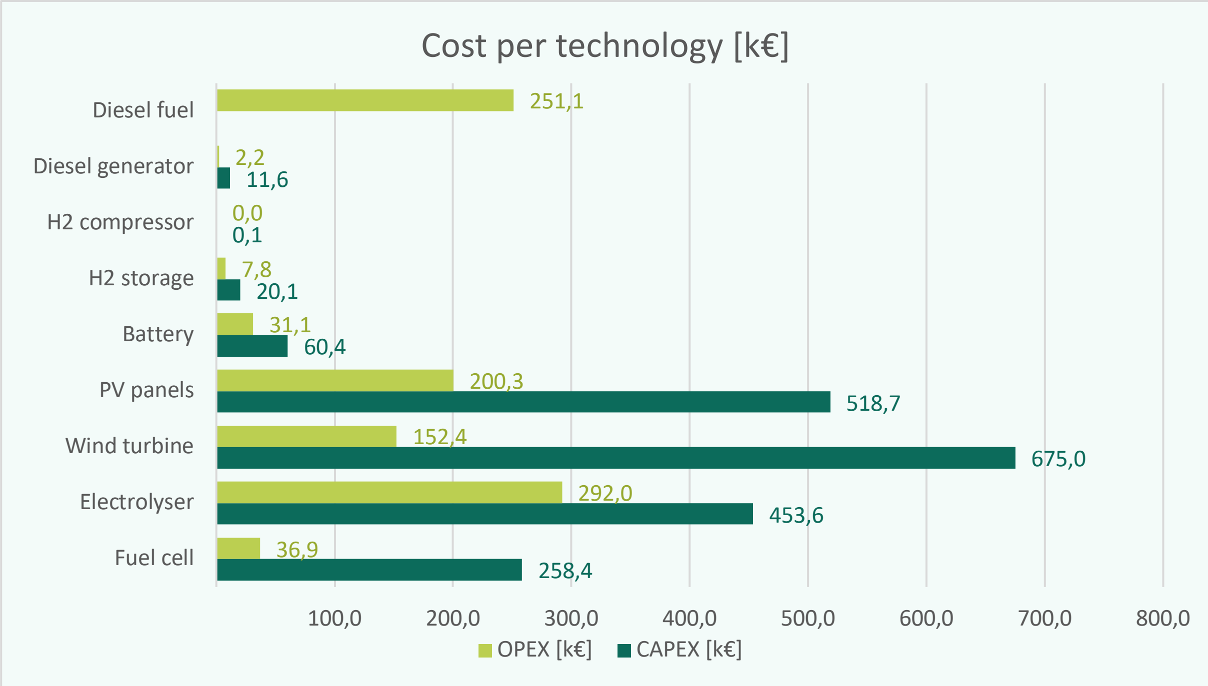

Figure 4.6: CAPEX and OPEX for each node during their entire lifetime

It could be useful to understand how each node interacts with the users to supply them the electricity. These data can clarify how much a particular device is used and how much it contributes to satisfy the load. Of course, all the electricity is produced by renewable sources or by back-up generators, but, in this chart, we consider the last device which supplies energy to the users. For example, if the wind turbine produces electricity, but then it is stored in the battery and, only later, this one supplies energy to the load, we consider this electricity coming from the battery. Figure 4.7 represents an example of this chart.

The following two charts (Figure 4.8) help us to understand better the flow of electricity between nodes. The first of two shows electricity flows from nodes which produce energy (wind turbines, photovoltaic panels, diesel generator). We can distinguish, for each node, flows of energy towards load, storage and curtailment. This chart highlights the share of each one in percentage but also the amount in MWh. The second one reports information about nodes which store energy (batteries, hydrogen system). In these systems, we consider all the electricity stored in them, which is equal to the amount of electricity leaving the previous nodes because transporting losses are not taken into account by the model. However, between charging and discharging, a certain amount of electricity is lost, depending on the kind of nodes. So, we distinguish between electricity which leaves the storage nodes to go towards users and electricity which is lost during storage.

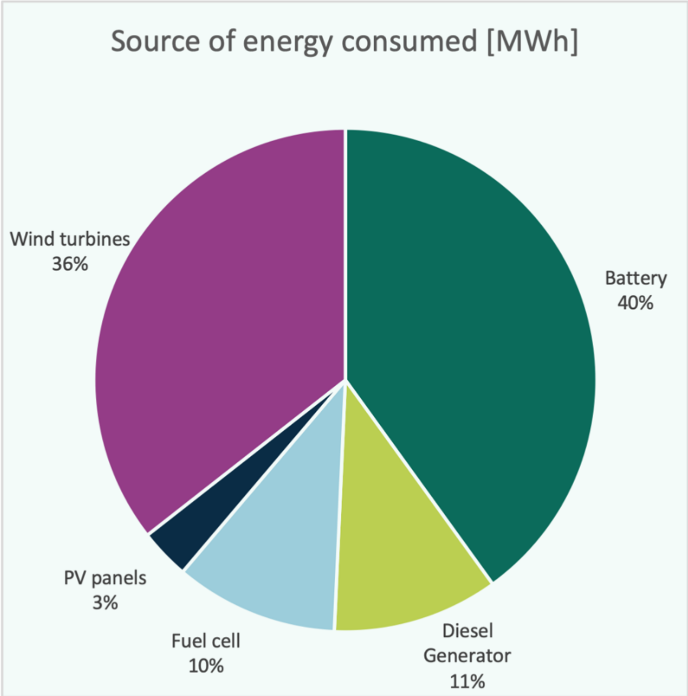

Figure 4.7: Share of energy by production

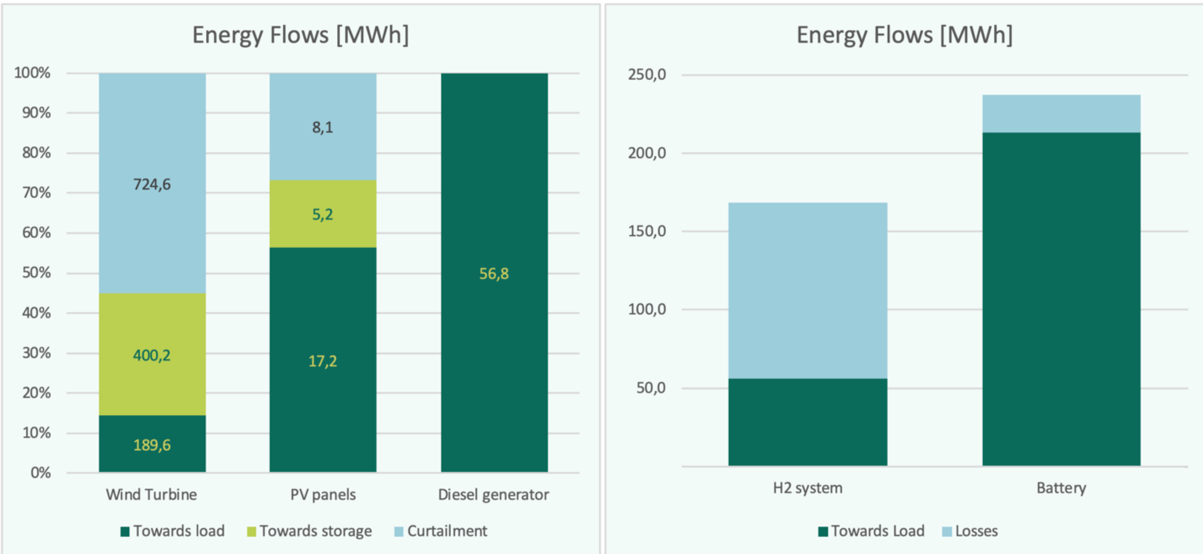

Figure 4.8: On the left, energy flows from WT, PV panels and DG (a). On the right, electricity flows from storages (b)

Subsequently, secondary products are reported in a panel. Here we can find the total amount of hydrogen and oxygen produced by the electrolyser. These data could be useful to consider possible profits if the user has the possibility to sell them. However, we should consider that, with the actual configuration of the model, all the hydrogen produced by the electrolyser is used in the fuel cell to meet the loads fully. Another secondary product is the heat from fuel cells and electrolysers, which could be recovered and reused inside the system for other purposes. In the same panel, we can find some data about sources used during the operation of the plant. First of all, water consumed by the electrolyser is reported in order to provide to the user an indication about the necessary water supply for the operation of the electrolyser. Then, in the event that a diesel generator is present, the panel displays the amount of fuel used. All these data refer to a single year, like for the flows of energy previously analysed.

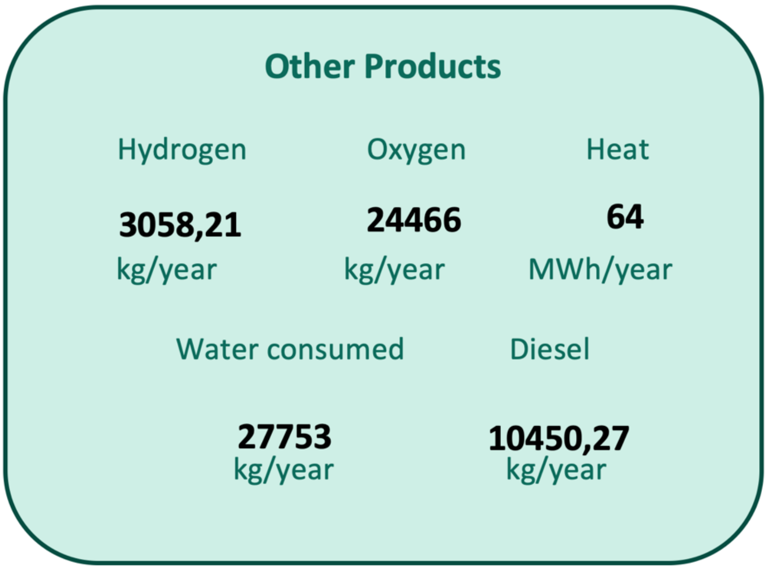

Figure 4.9: Secondary products and water consumption

The following two sheets report a simulation of the system operation displaying several profiles during the whole lifetime of the plant.

The first chart (name: "ResStorage") contains the storage profiles. The dark green line represents the hydrogen level in the tank and the light green line the charge of the batteries. It is possible to change the interval to show in the chart through a table. On top of the table, it is possible to select the strategic period. In the first row of the table, users can select the start day and hour of the period. If the user does not digit values for the hour, the model considers the beginning of the day (hour 0). In the second row, it is possible to do the same for the end of the period. Without indication about the end hour, the end of the final day is considered (hour 24). In the column of the days, the user can only insert values from 1 to 365 because data are available for a whole year of each strategic period. In the column of hours, it is possible to put a number from 0 to 24. There is a third column where the hours number of the year is automatically calculated for the beginning and the end of the period. In the same chart, there is also the profile of the load as reference. For long periods (>7 days), the horizontal axis reports indications of the number of the day, for short periods (< 7 days), it reports indication in hours.

Figure 4.10: Storage profiles' sheet

In the second chart (name: “ResPowerLoad”), we can see the power profiles hour by hour. The power output from the following nodes and directed toward users are reported in the chart:

- Wind turbines
- PV panels
- Fuel cell
- Battery
- Back-up generator (if any)

In the same chart, the power load is also shown. Values of electricity coming from a production node and headed towards storage have been subtracted. So, we can notice that the sum of the other profiles, for each hour, should be equal to the load, unless the system cannot satisfy the request of power. As for the previous sheet, it is possible to select the period in the same way. In the following pages, we can see two examples of these two charts.

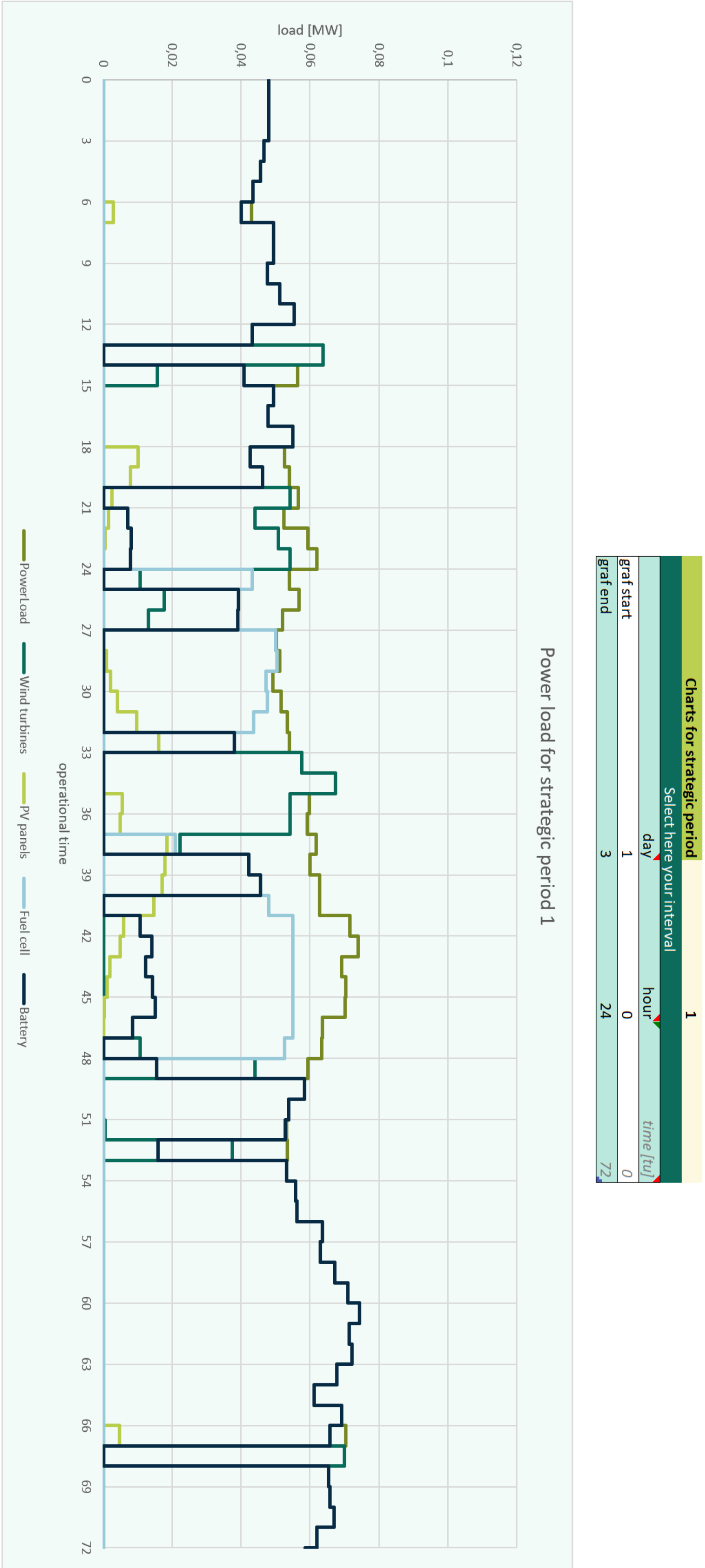

Figure 4.11: Power profiles' sheet

5. Description of the case study

5.1 Kökar Island

Kökar is a small archipelago municipality of Åland Islands. The Åland Islands is an archipelago province at the entrance to the Gulf of Bothnia in the Baltic Sea belonging to Finland. It is autonomous, demilitarised and is the only monolingually Swedish-speaking region in Finland [34]. The total area of Kökar municipality is 2165 km^2, but only 3% of the island's total area is landmass (64 km^2) [35].

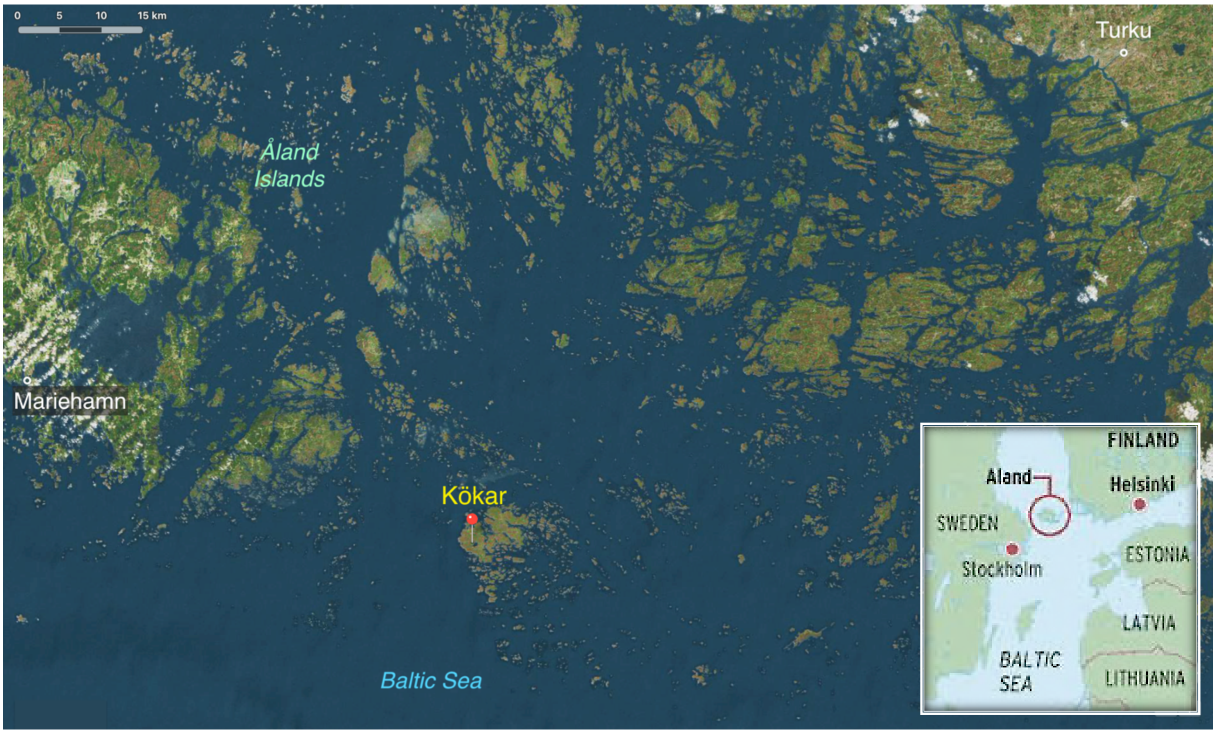

Figure 5.1: Localization of Kökar [36]

The population of Kökar island is officially 234 persons (2018), but politically speaking, the island is a full-scale municipality. Main economic activities are Seamen, agriculture, coast guard, bakery, tourism, public service. In reality, 160-170 persons live on Kökar wintertime, almost 1,000 summertime, and the island is visited by some 18,000 tourists per year, which makes a "technical population" of 467 persons [(170×365 days) + (1,000×90 days) + (18,000×1 day)]. This results in high volatility and puts extra demand on the flexibility of the infrastructure. A winter's day, some 170 people use the island systems, while they can be a couple of thousand in July. Kökar took part in the Clean Energy for EU Islands initiative [37] and published its clean energy transition agenda by summer 2020. Kökar has been selected as one of 20 islands in Europe that will act as pioneers in the work of reducing CO2 emissions.

Kökar is reachable by boat from Långnäs on Åland or from Galtby with access to mainland Finland [38]. The distance to Kökar is about 30 km with the ferry. There are two small industries in Kökar: a bakery which has its main markets in Finland and Sweden, and apple orchards which producer cider and apple juices, ditto. There are also three farms and some small service companies. We can count 121 residential buildings (93 small houses, 20 semi-detached houses, 4 multi-storey buildings) and 300 holiday-cottages. Tertiary sector facilities include a school, an elderly home, a vicarage, the bakery mentioned above, the Brudhäll Hotel, the Sandvik guest harbour & camping area and the Coast Guard station.

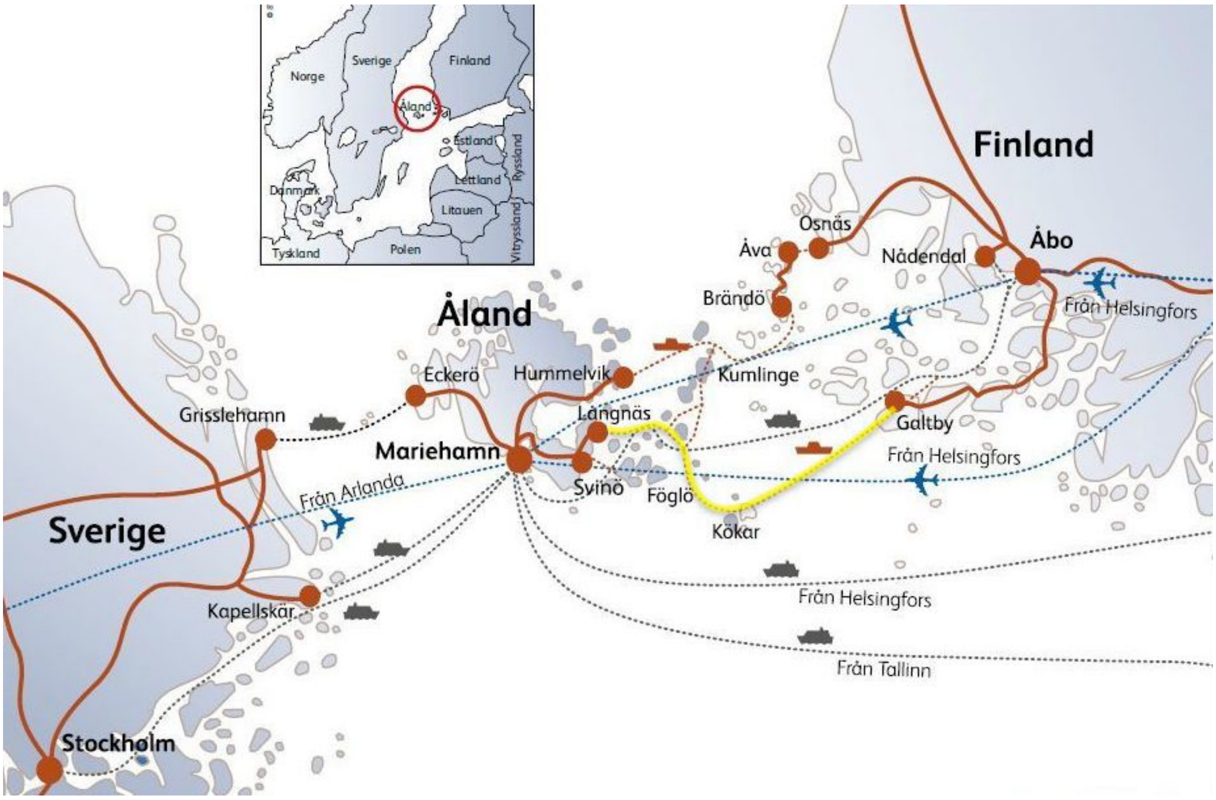

Figure 5.2: Connection to Ålands. In yellow ferry connection to Kökar [39]

5.2 Energy system configuration

The annual electricity consumption in Kökar is 2.9 GWh, with a peak load of 800 kW and a minimum of 400 kW. Ferry transport to and from the island accounts 1/3 of the total energy consumption. Except for the residential buildings, the principal consumers are the tertiary sector buildings. The school has a consumption of 25,000 litres oil per year, with a heating expenditure of 2000 €/month. Each building has a smart meter, with sending frequency 1/h. The DSO (Ålands Elandelslag, ÅEA) has installed smart meters in the whole Åland, which can handle bidirectional 15 minutes intervals. Each smart meter has a breaker to cut the grid connection. The smart meters also have built-in power quality measurement as well as the zero-error detection, and they can solve the zero-errors automatically. All the consumption data measured in the smart meters are sent via both cell radio and fibre cables to a datahub operated by Consilia Solutions AB.

Kökar is connected to the mainland by electric and telephone underwater cables. The capacity of the electric cable is 1.5 MW (Kökar-Sottunga-Gustavs). There is a weak grid connection with occasional outages (3-4 interruptions per year) in the distribution grid that cause local energy problems on Kökar. Reserve generators need to be taken to the island when there are outages (e.g. for the elderly home). There are ground heat pumps in 2 or 3 houses, and in the elderly home and vicarage. Many houses have switched to air-to-water heat pumps (the amount is not available). Around 70 houses use wood heating (some of them have hybrid heating combined with oil), and 47 buildings have oil heating. There are 401 electricity subscribers in Kökar, where 170 residential and 32 non-residential subscribers had electric heating. The hotel has an air-to-water heat pump of 16 kW.

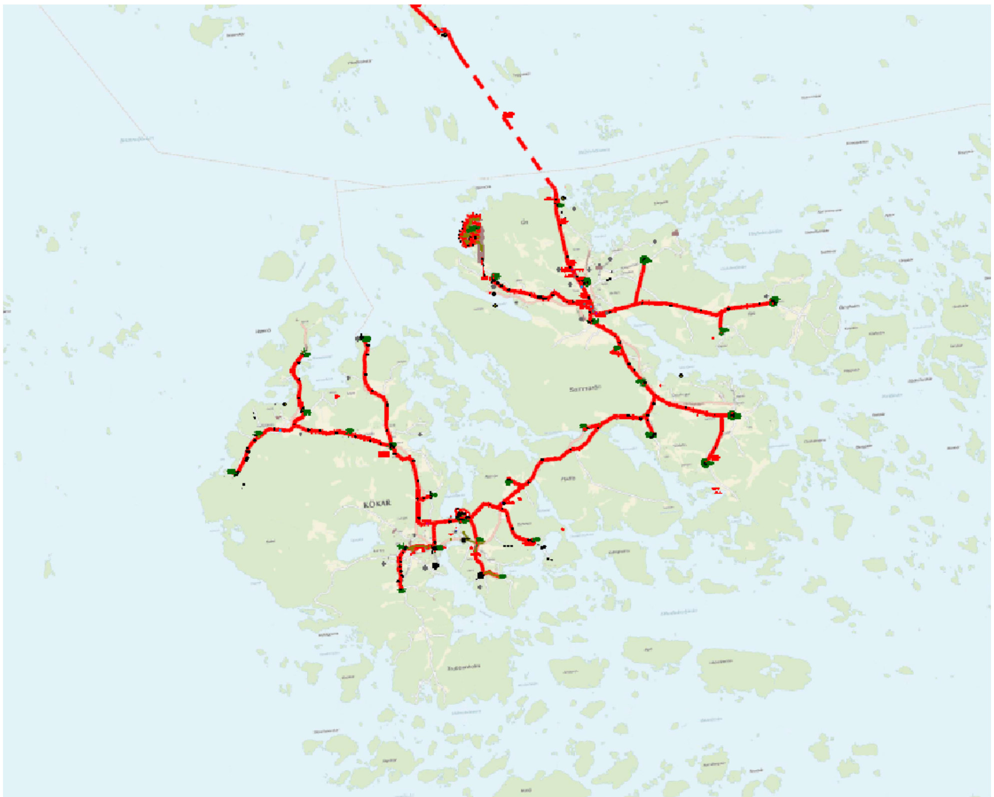

Figure 5.3: Kökar distribution grid (from KTH report)

Some houses and tertiary buildings have PV panels, with a total installed capacity of 39.1 kW. There are also 35 kW micro-wind installed in two private houses. On the island, a wind power plant called "Mika" is also present, with an installed capacity of 500 kW. Its annual production is approximately 1163 MWh, so around 40 % of the electricity consumption of the island. Further information about the wind farm are shown in Table 5.2.

Energy asset	Power [kW]	Owner
PV (residential)	**18.1** (1.5+11.4+5.2)	Private houses
PV (tertiary)	**21** (5.2+3.6+3.2+9)	Boutique, bakery, Kökar Service, accommodation service "Skinnars"
Micro-wind (residential)	**35** (15 + 20)	Private houses

Table 5.1: PV panels and micro-wind turbines installed in Kökar

“Mika” wind farm, Kökar, Finland	
Commissioning	1997/10
Turbine model	Enercon E40/500 (power 500 kW, diameter 40 m)
Hub height	44 m
Total nominal power	500 kW
Status	Operational
Site	Onshore wind farm
Operator	AVA
Owner	AVA

Table 5.2: Kökar wind farm, general data [40] [41]

In the next table, we can find the energy consumption for Kökar. The table shows electricity, oil and biomass consumption in several applications, and for each of them, it reports the CO_2 emission.

Current situation			
Energy consumption			CO_2 emissions [ton $CO_{2,eq}$]
Oil (heating)	Houses	24 000 l/year	62.8
	School	25 000 l/year	
Biomass (heating)	Houses (firewood)	2627 m^3	
	Bakery (pellet)	1500 kg/year	
Electricity	Electric heated houses	1625.5 MWh/yr	109.9
	Holiday cottages	436.9 MWh/yr	29.5
	Other	893.6 MWh/yr	60.4
	Total	**2,956.0 MWh/yr**	**199.8**

Table 5.3: Kökar energy consumption (from KTH report)

In this table, emission and consumption due to transportation are not considered. Regarding maritime traffic, in addition to ferries and other commercial traffic boats, we also have to consider the private traffic and the border guard. Besides, on the island, there are several vehicles:

- 1 bus
- 3 quad bikes
- 10 trucks
- 9 light quad bikes
- 45 mopeds
- 10 motorcycles
- 55 package cars
- 162 passenger cars
- 88 tractors
- 1 e-car

5.3 Data and scenarios

Kökar data has been provided by KTH University. Regarding hourly load data, they were available for a whole year (2017) except for January. However, it is necessary to have data for every hour of the year, so it has been supposed to have the same load in February and in January. As it has been said, the population in Kökar varies due to tourism during summer, but in wintertime, it is not reasonable to expect significant fluctuations in the load because the population is constant. There could be higher consumption in January compared to February due to fewer hours of daylight and lowest temperature, but without indication to estimate them, we consider this variation negligible. In fact, the yearly consumption which is calculated from this profile is around 2.8 GWh, and we know that the real consumption is close to this value (2.9 GWh).

Regarding wind data, KTH provided data from Mika wind farm in Kökar. Data is missing from the 1st of January to the 13th of February 2017. It was necessary to estimate the wind production in this period, and the website *Renewable.ninja* [42] has been used. The website requires the following information:

- Location
- Capacity
- Hub height
- Turbine model

The same features of Mika have been used, except for the capacity. In fact, a unit value of 1 kW has been inserted obtaining the production rate directly. The website then produces a CSV file with the hourly wind production in kW for a whole year, in particular for 2014, which is the only available year in the database. Comparing the official data with data from *Renewable.ninja*, the firsts are on average 1.75 bigger than the second and maybe one of the causes is that they refer to a different year. However, although with a probable underestimation, the data from the website have been inserted in the official dataset to have a full year. The wind production from KTH University has been previously divided by the capacity to get the production rate.

Although there are some photovoltaic panels on the islands, information about their production has not been provided. In order to estimate the production of the already existing panels and of the possible new, it was necessary to consult another tool available on the European Commission website and called *PVGIS* (Photovoltaic Geographical Information System) [43]. *PVGIS* allows getting various information about solar radiation and power production from photovoltaic panels in a selected site. In this case, it has been used to gain hourly radiation data for a whole year specifying the following information:

- Location
- Solar radiation database: PVGIS-SARAH
- Start and end year: 2016 (the latest available)
- Mounting type: fixed with optimised slope and azimuth

The tool produces a CSV file with hourly irradiance data in W and also, for each hour, it provides the Sun height (degree), the 2-meter air temperature (°C) and the 10-meter wind speed (m/s).

All these profiles have been used in all the following scenarios.

Several scenarios have been tested to evaluate the operation of the new tool developed in different situations. We wanted to analyse the configuration of a hybrid system which supplies energy to every load without the support of energy from the existing submarine cables and using only renewable sources. In each scenario, the same base configuration has been considered: photovoltaics panels and wind turbine for power production, hydrogen system and batteries for the storage. CAPEX and OPEX data have been selected from tables in the Excel sheet "Economic input", and they are reported in the Table 5.4. In the sheet "Advanced input", the existing capacities for photovoltaic panels and wind turbine have been entered but neglecting the micro-wind of which we do not know the production or the model.

Node	CAPEX	unit	OPEX	unit
Battery (Li-ion LFP)	549.1	[€/kWh]	4 %	[% of CAPEX]
Electrolyser (PEM)	1226.2	[€/kW]	3 %	[% of CAPEX]
Fuel Cell	5109	[€/kW]	5 %	[% of CAPEX]
Compressed H_2 storage	408.7	[€/kg]	0 %	[% of CAPEX]
Hydrogen compressor	19724	[€/kg/h]	4 %	[% of CAPEX]
Wind Turbine (onshore)	1273	[€/kW]	42.7	[€/kW yr.]
PV panels (Rooftop-C&I)	2115	[€/kW]	16	[€/kW yr.]

Table 5.4: Selected data for the analysed scenarios

Besides, a non-binary investment has been considered because, in this phase of the analysis, we do not know the size of possible systems which can be used. So, the results will not show the real capacity to install, but an ideal situation with the possibility to add capacity in a continuous mode. However, this analysis can be useful to compare the effect of different requirements on the results and to obtain a first approximated sizing of the system.

As regards the time, two strategic periods, each lasting 10 years, have been chosen. This is the already present option in the model, and it has been used for the DEMO case studies. It has been chosen not to change it because no different information has been provided. For the same reason, the real discount rate is what it was previously implemented, and it is equal to 0.049. This value has been used by the model in the optimisation of the system, based on minimising the net present value (NPV).

In the next chapter, we will see the results for the several scenarios analysed. In particular, in the following scenarios, different demands to satisfy have been considered:

- Total electric loads
- Total electric loads + electric mobility
- Total electric loads + hydrogen mobility
- Total electric loads + substitution of old heating systems with heat pumps ("electric heating")
- Total electric loads + electric mobility + "electric heating"
- Total electric loads + hydrogen mobility + "electric heating".

6. Case study results

6.1 Scenario 1: total electric loads

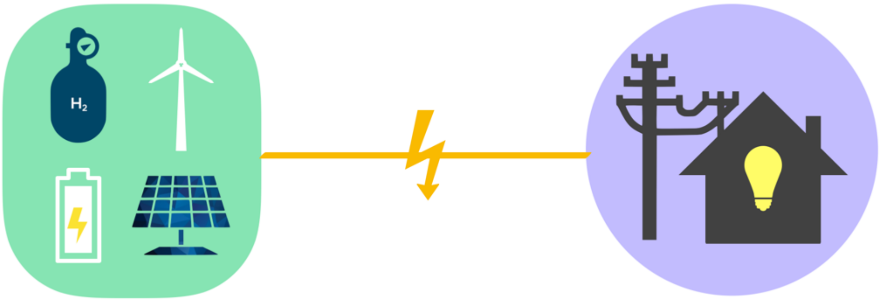

Figure 6.1: Scenario 1 configuration

In the first scenario, it has been supposed to satisfy all the electric loads with a hybrid plant, ensuring the independence of the island from the mainland. At present, a submarine cable provides part of the electricity to Kökar, but in this analysis, this contribution has not been considered.

The simulation resulted in a Levelized Cost of Electricity (LCOE) of 0.349 €/kWh. Capacities and costs of the nodes are shown in Table 6.1 and Figure 6.2.

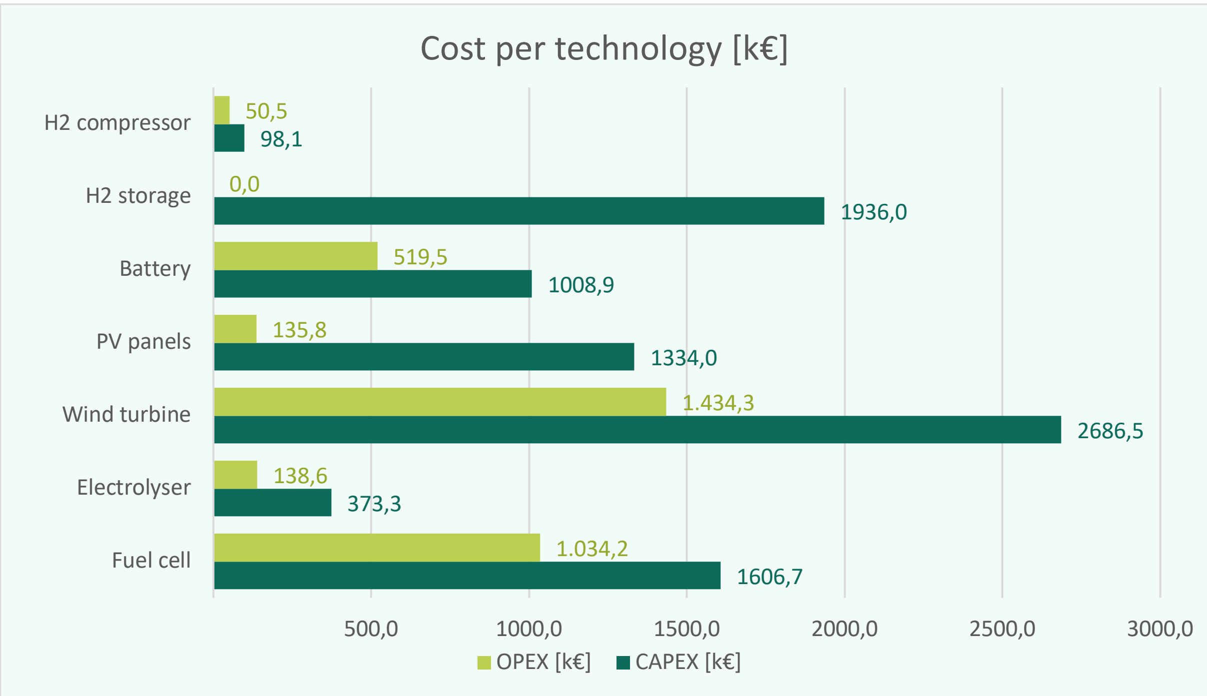

Figure 6.2: CAPEX and OPEX of the nodes (scenario 1)

Node	Capacity	Unit
Fuel cell	314	kW
Electrolyser	273	kW
Wind turbine	2610	kW
PV panels	670	kW
Battery	1837	kWh
H2 storage	4737	kg
H2 compressor	5	kg/h

Table 6.1: Nodes size (scenario 1)

In the table, the indicated capacity is the total, including the existing capacity. So, according to this simulation, for the wind turbine, the installed capacity is more than four times the existing one. If the new turbines were of the same model as the older ones, it would be necessary to install at least four new wind turbines (even with a surplus to be covered differently). Furthermore, the role of the solar power would not be negligible, with 670 kW of total photovoltaic panels installed against compared to the 39.1 kW in the current situation. It is also possible to notice its importance in the next figures.

The most relevant cost regards the wind turbines, due to the large installed capacity. However, the incidence of the hydrogen system is very important, in particular, due to the high cost of the fuel cell and of the hydrogen storage, which is enormous.

Although the wind turbines produce the majority of power, the role of the PV panels is relevant. Almost 58 % of the energy produced by the wind turbines is directly sent to the loads (1554.8 MWh), and a similar amount of energy goes to the storage (1732.5 MWh). The share of electricity directed to the load and coming from the PV panels is 9 % (249.5 MWh), while a smaller quantity (148.2 MWh) flows towards storage systems. The role of the storage systems is relevant, because together they supply around 33 % of electricity to the load, with almost equal contributions, 16 % from batteries (433.0 MWh) and 17 % from fuel cell (444.3 MWh). However, the efficiency of the two systems is very different. Between charging and discharging, the amount of energy lost by the battery is around 48.1 MWh compared with the 955.3 MWh of the hydrogen system. The causes of these losses are the efficiency of the electrolyser to convert electricity to hydrogen and then the efficiency of the fuel cell to do the opposite. Nevertheless, it is convenient to use also a hydrogen system to avoid a too big size of the battery and also because it is useful to store energy for long periods.

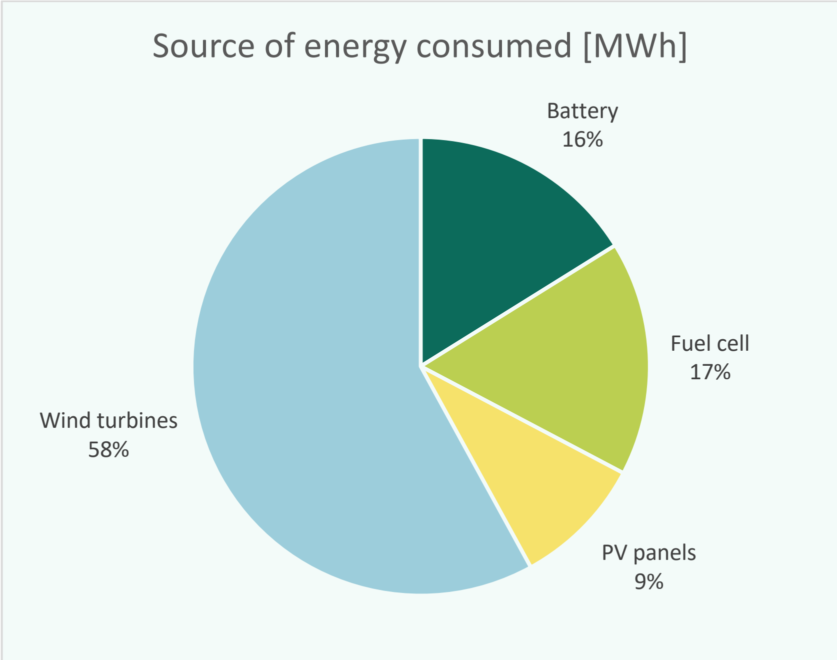

Figure 6.3: Shares of electricity from nodes (scenario 1)

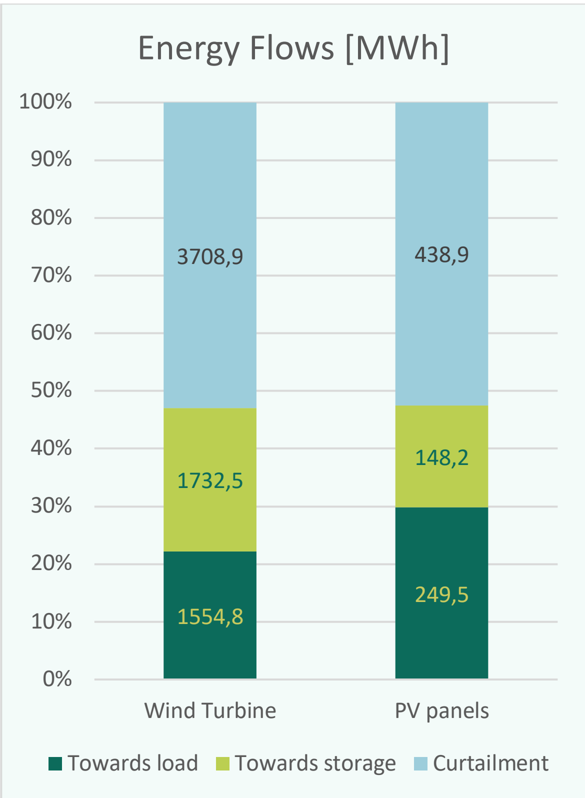

Figure 6.4: Flows of energy from production nodes (scenario 1)

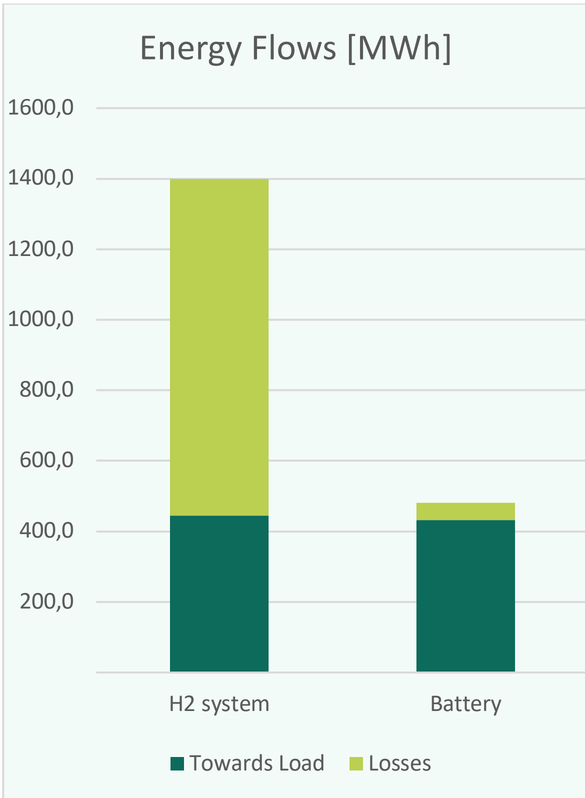

Figure 6.5: Flows of energy from storage nodes (scenario 1)

Finally, the next panel shows the other products of the system (hydrogen, oxygen, heat) and the consumption of water. The electrolyser consumes around 632 kg per day of water that is a relevant quantity to consider if one wanted to build a system like this. For example, a Finnish citizen consumes an average of 0.15 kg/day of water for drinking, cooking and household needs [44].

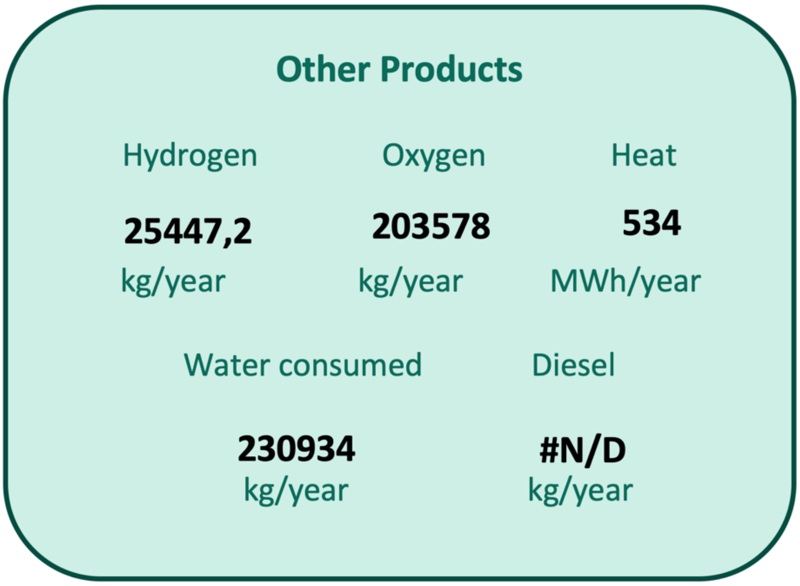

Figure 6.6: Other products and water consumption (scenario 1)

6.2 Scenario 2: total electric loads and electric mobility

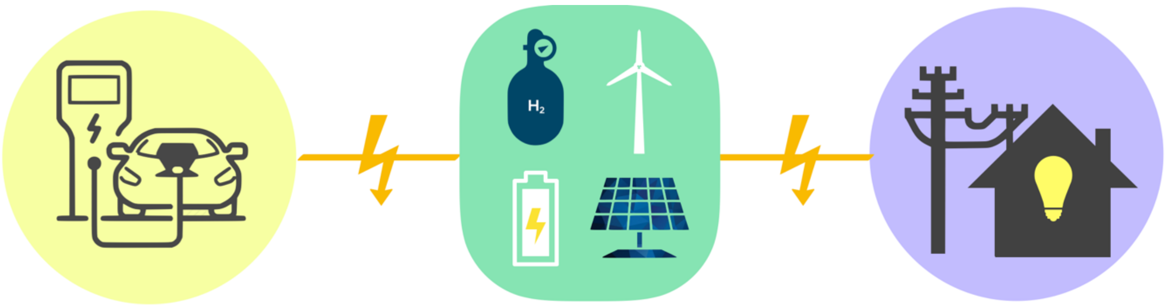

Figure 6.7: Scenario 2 configuration

This scenario evaluates the conditions to satisfy all the loads on the island if the current mobility was composed of only electric vehicles. The present configuration of the traffic has been shown in the previous chapter. It has been supposed that all those vehicles were replaced by the same number of electric vehicles, except for the tractors, which traffic is difficult to estimate and so they have been ignored in this analysis. It has been assumed an average consumption of these electric transportations of 0.2 kWh/km [45] and that the ordinary journey of each one was 41 km, like in the rest of Finland [46]. This value is almost certainly overestimated because, on a small island, the average length of the journeys is probably shorter than in the mainland, and because not all vehicles could be used every day. Besides, the typology of vehicles is varied, so consumptions and ways of use could be very different. However, without further information, the analysis has been made using these approximations.

A daily charging profile for electric vehicles has been created. It has been assumed that during the night (between 19:00 to 5:00), each inhabitant recharges the amount of electricity consumed during the day. According to the previous assumption, each vehicle consumes 8.2 kWh, so it is necessary to provide around 820 Wh per hour during the night. This value is reasonable, because the charging speed for an electric car is around 3,7 kW per hour, charging it to the home power outlet [47]. The daily profile has been obtained considering the total amount of vehicles (295 without tractors), and it is shown in Table 6.2. This profile is valid if the amount of electricity levied was constant per each hour and during the whole year. However, this is also an approximation because the population varies through the seasons and, therefore, even the traffic. Once this profile has been obtained, it has been added to the previous profile of the current electric load, and the new profile has been entered in the “Profiles” sheet.

Hour	kWh	Hour	kWh	Hour	kWh	Hour	kWh
00:00	241,9	06:00	0	12:00	0	18:00	0
01:00	241,9	07:00	0	13:00	0	19:00	241,9
02:00	241,9	08:00	0	14:00	0	20:00	241,9
03:00	241,9	09:00	0	15:00	0	21:00	241,9
04:00	241,9	10:00	0	16:00	0	22:00	241,9
05:00	0	11:00	0	17:00	0	23:00	241,9

Table 6.2: Daily profile for electric vehicles

The LCOE of this scenario is 0.328 €/kWh, and it is lower than the previous one. The yearly electricity requirement is obviously higher than before, and it passes from 2.8 GWh to 3.7 GWh. Accordingly, the capacity of the equipment increases, except for the hydrogen storage, as we can see in Table 6.3. Therefore, there is a rise in cost per node, as reported in the following figure.

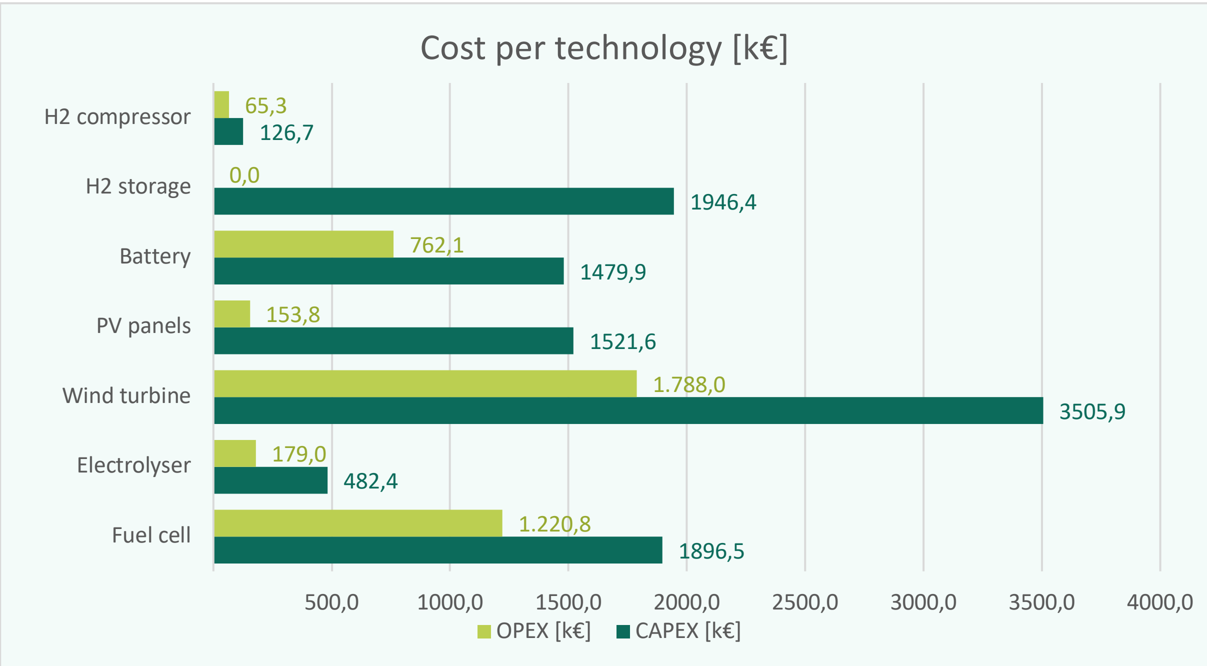

Figure 6.8: CAPEX and OPEX of the nodes (scenario 2)

Node	Capacity	Unit
Fuel cell	371	kW
Electrolyser	353	kW
Wind turbine	3254	kW
PV panels	759	kW
Battery	2695	kWh
H2 storage	4762	kg
H2 compressor	6	kg/h

Table 6.3: Nodes size (scenario 2)

The lower value for the LCOE could be caused by a difference in the flows of energy. Looking at the share of electricity per node, it is similar to Figure 6.9, but there is a slight increase in the amount of power directly supplied by the wind turbine (60 %), and also the curtailments decreased (Figure 6.10). In this way, less energy is wasted because, if it passes through the storage, a certain amount is lost due to efficiency. Besides, the system stores more energy in the battery (590.8 MWh) than in the hydrogen (548.7 MWh), with an increase of the efficiency. The best exploitation of the resources of scenario 2 could originate from the lesser variability of the load within 24 hours. The surplus of demand in the hours of the night (between 19 and 5), could favour the direct exploitation of a large part of the energy produced by wind turbines that would otherwise be lost or stored in storage.

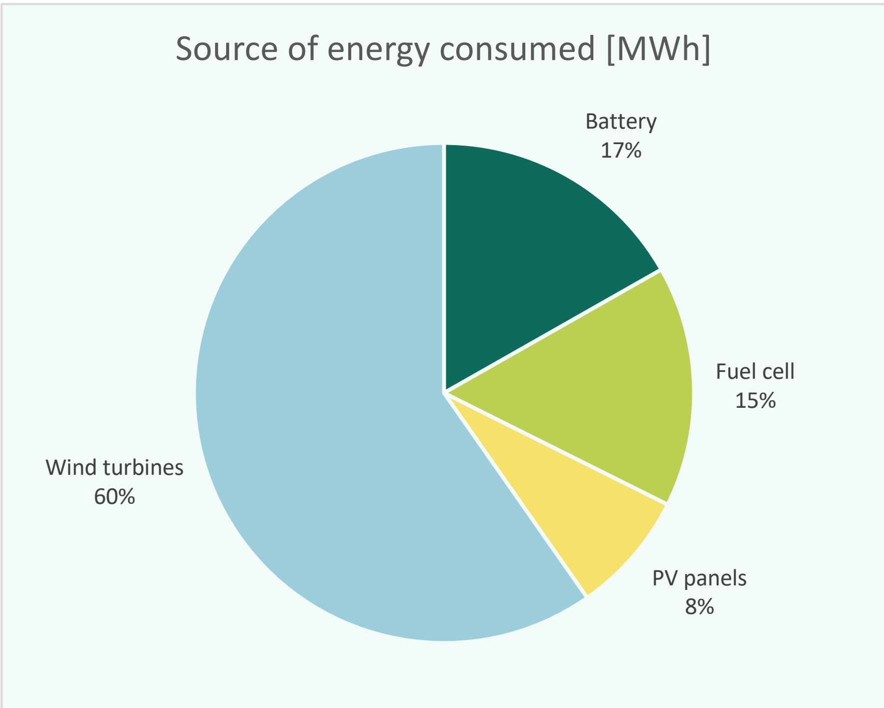

Figure 6.9: Shares of electricity from nodes (scenario 2)

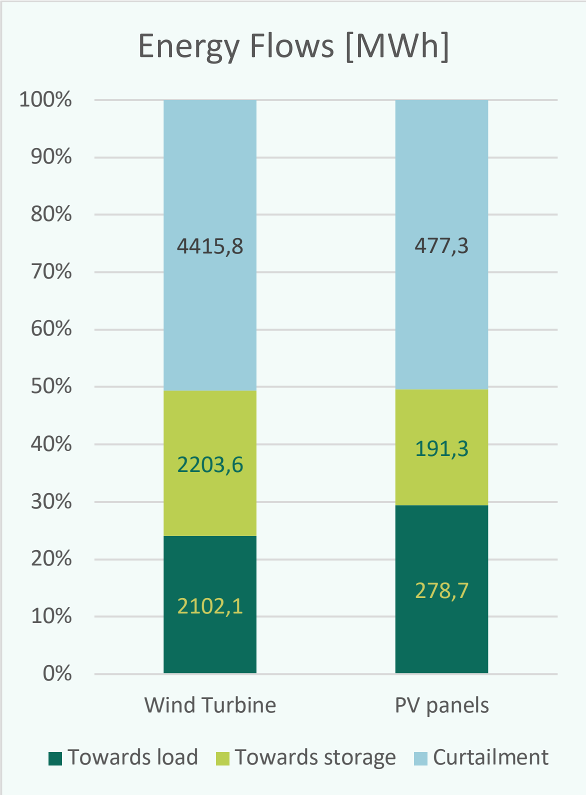

Figure 6.10: Flows of energy from production nodes (scenario 2)

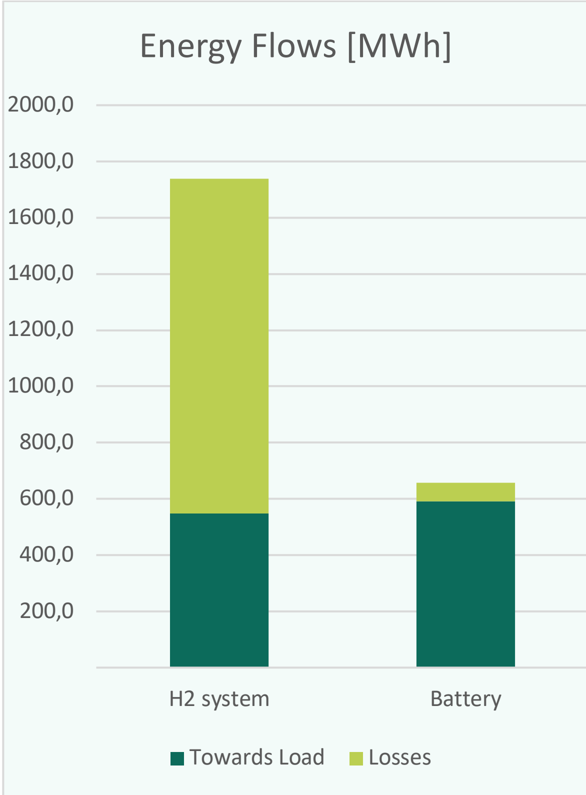

Figure 6.11: Flows of energy from storage nodes (scenario 2)

Finally, in the following panel, we can see as the secondary products and the exploitation of the water increase due to the greater size of the electrolyser and of the fuel cell, which manage a higher quantity of energy.

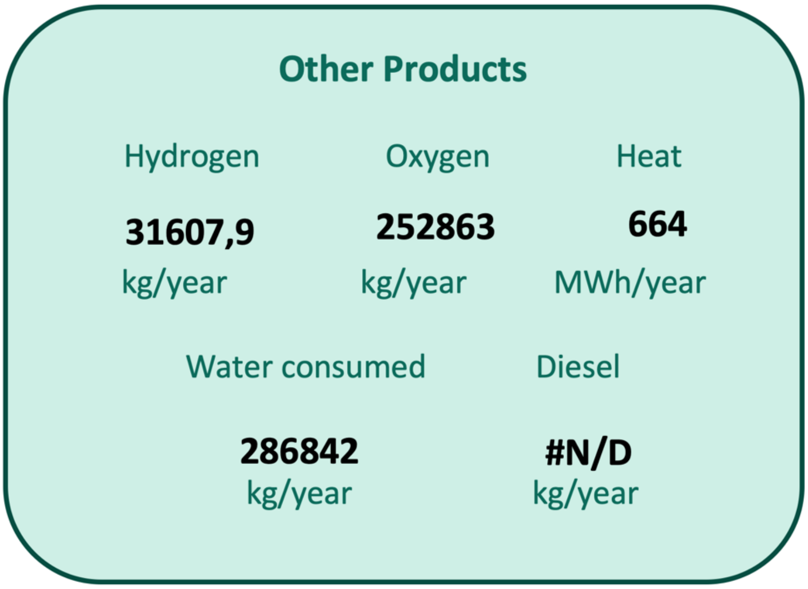

Figure 6.12: Other products and water consumption (scenario 2)

6.3 Scenario 3: total electric loads and hydrogen mobility

Figure 6.13: Scenario 3 configuration

The adoption of hydrogen-based mobility could represent an alternative to the previous case. Surplus of energy, instead of being used to charge electric vehicles or wasted, could be stored in the form of hydrogen by electrolysis, which can be used as fuel for the transportations. Hydrogen vehicles, as for those electric, do not produce CO_2 or pollutants. In fact, the hydrogen is stored into a tank, and it is used by the fuel cells to produce electricity for the electric engine. The advantage of these vehicles is that the refuelling times are shorter compared to those electric. A hydrogen car uses 3 to 5 minutes to recharge the pressure tank (usually at 700 bar) with 4 to 7 kg of fuel, compared with the hours to fully recharge the batteries of an electric car, ensuring a similar value of autonomy [48]. However, it is also necessary to install a refuelling station, which is not considered in this analysis.

As for the electric vehicle, it was necessary to estimate the hydrogen requirements on the bases of the traffic on the island. The same assumptions of the previous scenarios have been taken regards average journey distance (41 km) and the number of vehicles (295). The Toyota Mirai is one of the few hydrogen cars in Europe, so its consumptions have been taken as reference. Considering that a vehicle uses around 7.6 g of hydrogen per kilometres (131 km/kg) [49], the total yearly requirement is around 33546 kg. It has been supposed a constant demand for hydrogen for all the hours of the year (3.83 kg/h).

It is necessary to modify the interface to satisfy this requirement. The model can accept a demand for hydrogen, but it needs an hourly profile. This profile has to be placed below the load profile in the old Excel file of the model. So, in the "Profile" sheet, a new table has been added to enter the hydrogen requirements data, and these cells have been linked with that of the pre-existing sheet.

As we can notice in Table 6.4, the capacity of the electrolyser and the hydrogen tank increased significantly because in comparison with scenario 2. This is reasonable because more hydrogen is produced and stored to refuel the vehicles or to be converted into electricity. Instead, the fuel cell has the same purpose as before, that is electricity production. For this reason, its capacity does not vary a lot, indeed, it is slightly lower than in scenario 1 (314.5 kW). The size of wind turbines, photovoltaic panels and batteries increased too, but it is smaller than in scenario 2. Capacities and costs are reported below.

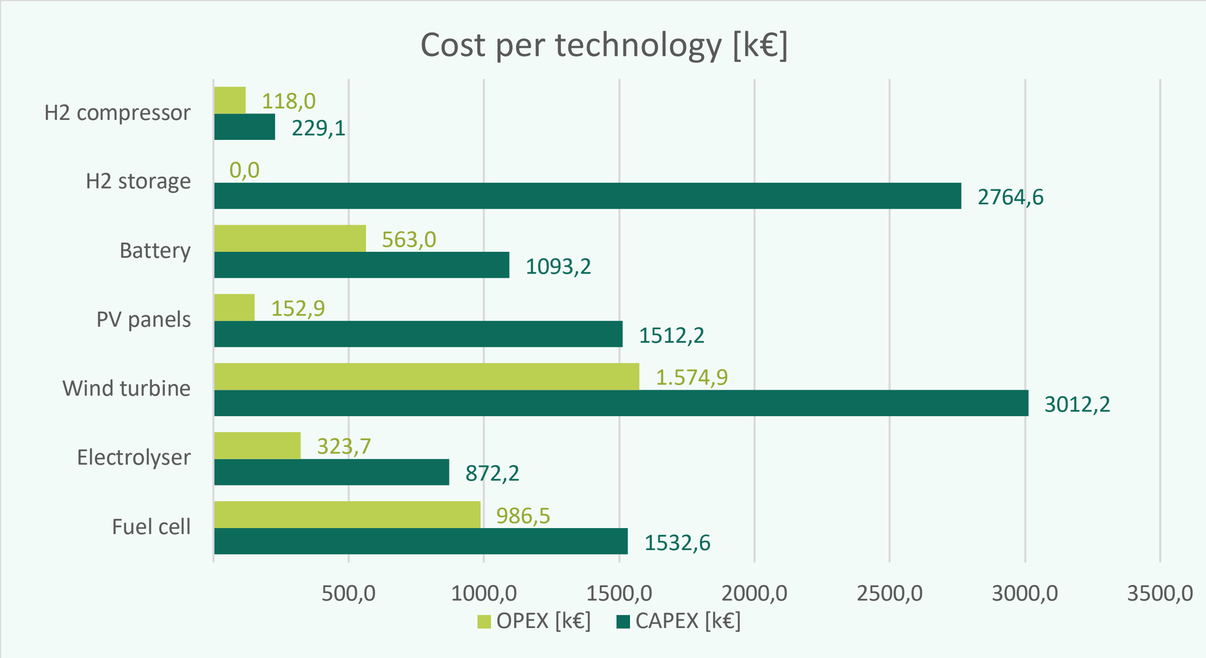

Figure 6.14: CAPEX and OPEX of the nodes (scenario 3)

Node	Capacity	Unit
Fuel cell	300	kW
Electrolyser	639	kW
Wind turbine	2866	kW
PV panels	754	kW
Battery	1991	kWh
H2 storage	6764	kg
H2 compressor	12	kg/h

Table 6.4: Nodes size (scenario 3)

The LCOE increased significantly (0.421 €/kWh) because, compared to the previous scenarios, the system is not exclusively designed to supply electricity, and this parameter does not take into account this factor. Another parameter has been calculated to estimate the economic value of the hydrogen produced. This parameter is the Levelized Cost of Hydrogen ($LCOH_2$), and the formula is the following:

$$LCOH_2 = \frac{\sum_{i=1}^{sp}[Dis_{st} \cdot CAPEX_i + Dis_{av} \sum_{a=1}^{t} OPEX_{a,i} + \sum_{a=1}^{t}\left(\frac{RC_{a,i}}{(1+d)^{a+(i-1)t}}\right)]}{Yearly\ hydrogen\ delivery \cdot \frac{1-(1+d)^{-sp \cdot t}}{d}} \quad (6.1)$$

As we can notice, the formula is the same as for LCOE, with the yearly hydrogen delivery instead of the yearly energy delivery. However, it must be pointed out that are not considered CAPEX, OPEX and regeneration costs (RC) of the battery, because it should not have an active role in the production of hydrogen. The yearly hydrogen delivery represents only the amount of hydrogen intended for the transportations. The value of the $LCOH_2$ is 28.88 €/kg_{H2}. This value is higher if compared with the price of hydrogen in Finland for transportation, which is 5-10 €/kg_{H2} [50]. As for the LCOE, we must consider that this value is distorted if we consider that the size of the equipment is justified by the fact that it also covers other functions. It could be useful to consider a corrected parameter that takes into account as much the operation of a node serves to supply electricity or to produce hydrogen for the refuelling station, but it is difficult to obtain this kind of data.

The shares of electricity directed to the loads are almost the same as the first scenario, with a slight rise of the energy produced by the photovoltaic panels (12 %) at the expense of those provided by the storage. It is important to notice as the significant reduction of the curtailments (Figure 6.16), both for wind turbines and PV panels. We can register a reduction of almost 15 % compared to scenario 1 and more than 10 % to scenario 2. This is reasonable if we think that, to cover the same purposes, scenario 3 requires a smaller capacity for the wind turbines and almost the same for the PV panels. In this way, less amount of available energy is lost because it can be used to produce hydrogen.

Looking at Figure 6.17, the losses of the hydrogen system would appear a lot, but this data is not real. The chart does not consider that a certain amount of hydrogen is produced as fuel, so it has not been converted into electricity by the fuel cell, and for this reason, it appears as a loss.

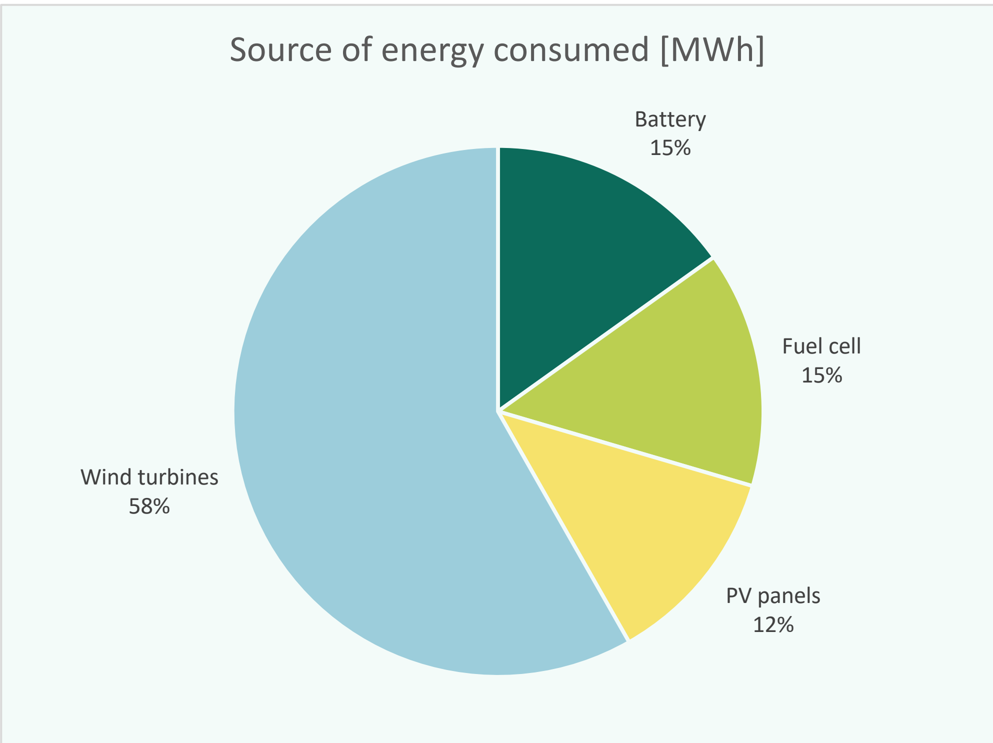

Figure 6.15: Shares of electricity from nodes (scenario 3)

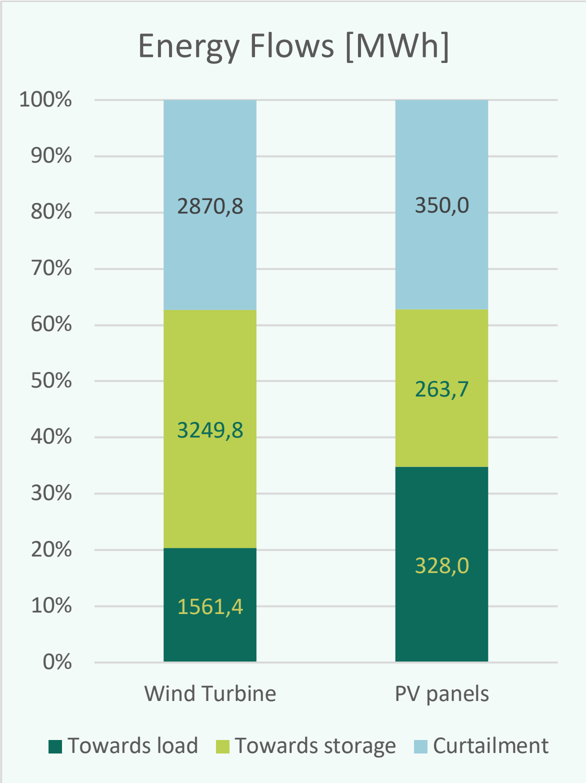

Figure 6.16: Flows of energy from production nodes (scenario 3)

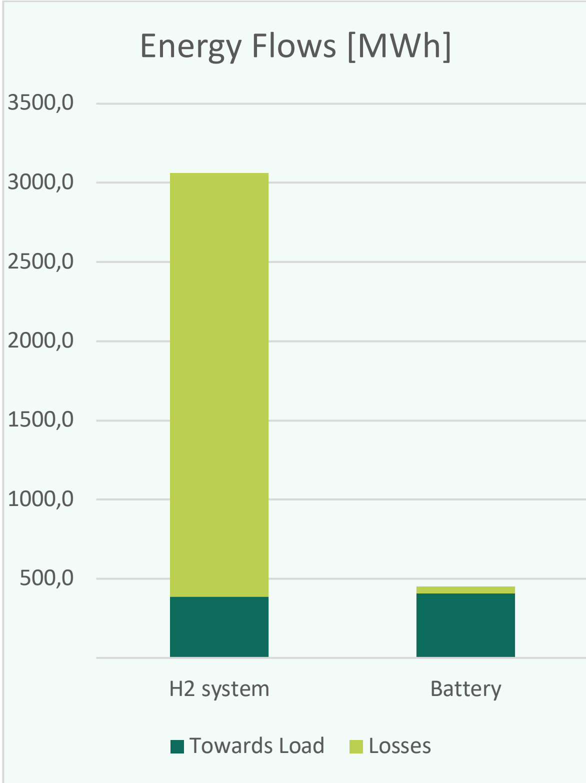

Figure 6.17: Flows of energy from storage nodes (scenario 3)

In the next panel, the value of hydrogen also includes the amount of fuel for the vehicles but, removing this quantity (33546 kg), the remaining value is similar (slightly lower) to scenario 1 (25447 kg). As a consequence, the electrolyser consumes much more water than in scenario 1 but also produced a considerable quantity of secondary products (heat and oxygen), which can have a significant role for other purposes, even from an economic point of view.

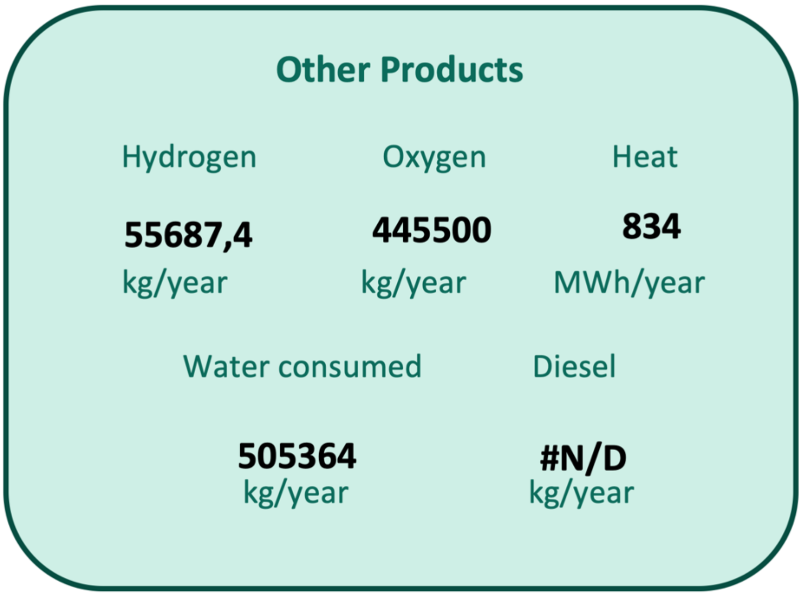

Figure 6.18: Other products and water consumption (scenario 3)

6.3.1 Alternative scenario 3

To provide a constant flow of hydrogen for all hours in a year could be a too hard constraint. For this reason, an alternative scenario has been evaluated. In this case, all the daily hydrogen requirement (around 91.9 kg) has been concentrated in an hour. The chosen hour is 23:00 and, during the rest of the day, the hydrogen requirement from the refuelling station is zero. However, the size of this system is almost the same as the previous one, as we can notice from Figure 6.17. Only the photovoltaic panels recorded a decrease in the installed capacity because there is no more need to satisfy the demand of hydrogen during the day constantly. It follows that also the LCOE is almost identical, with a minimal increase (+ 0.001 €/kWh). Since there are no major differences, we will continue to take the first case as a reference. The other charts of this alternative scenario have not been reported because they show the same features of those previously reported.

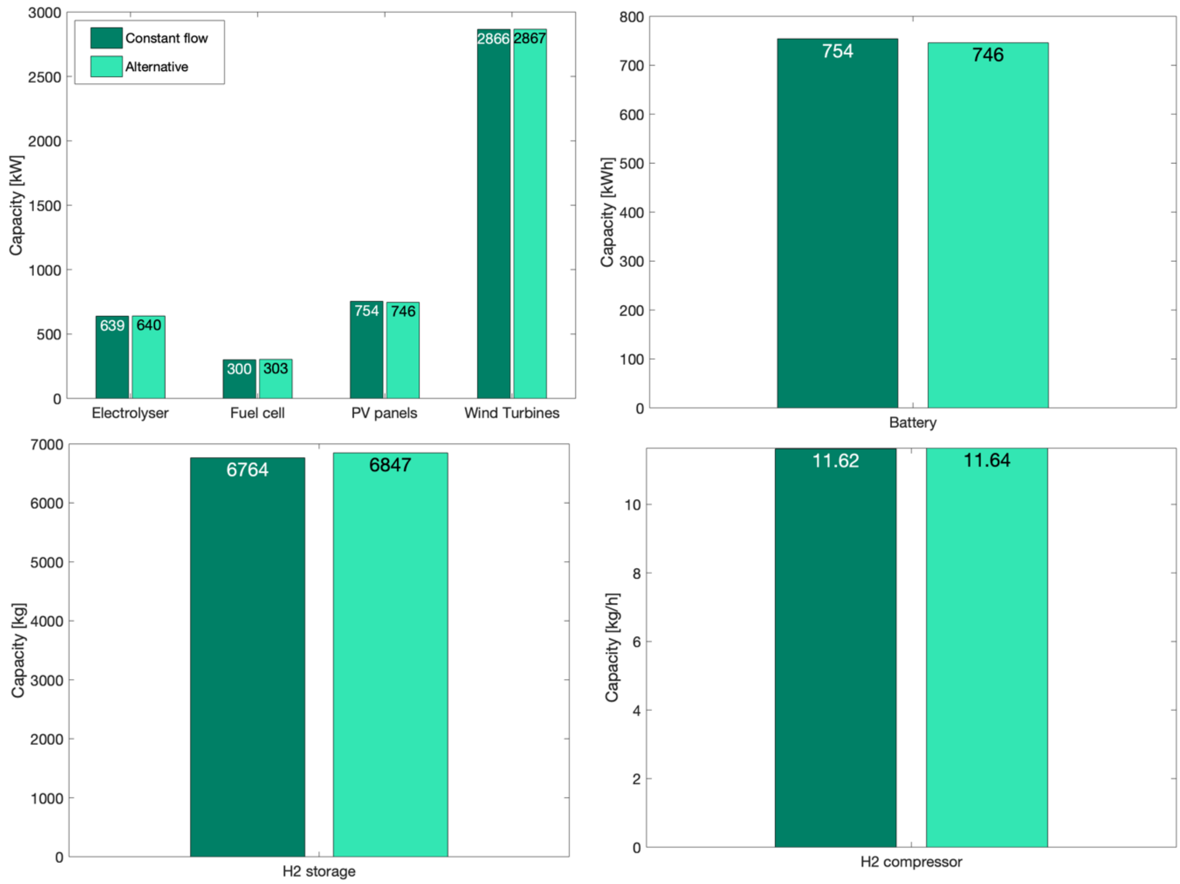

Figure 6.19: comparison between the two alternative scenarios

6.4 Scenario 4: total electric loads and electric heating

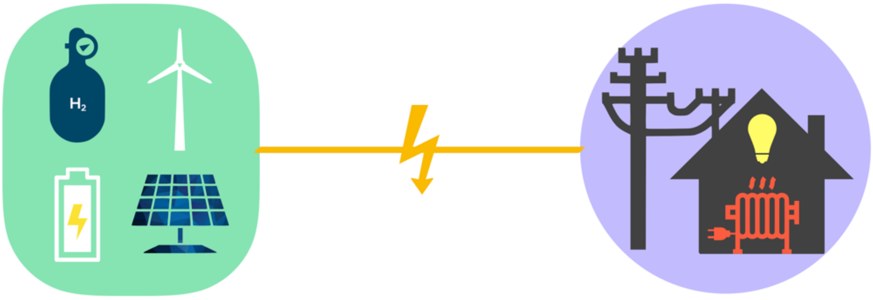

Figure 6.20: Scenario 4 configuration

As we saw in paragraph 5.2, many buildings use oil gas or biomass for heating, and this produces 62.8 ton $CO_{2,eq.}$ In this scenario has been evaluated the sizing of a system which can satisfy the current loads and the additional loads if the buildings mentioned above adopted heat pumps. Heat pumps would operate with the electricity produced by renewable sources, saving a significant amount of emissions. Table 6.5 reports the current situation in Kökar as regards the heating typologies. On the island, out of 233 buildings, 43 uses oil gas for heating and 43 wood. We have no information about 29 buildings, and it has been supposed that they are heated with wood.

Buildings	Total	Oil gas	Electricity	Wood	Ground heat	Other
Total	233	47	107	43	7	29
Detached and semi-detached houses	168	41	71	42	2	12
Attached houses	6	0	3	0	3	0
Blocks of flats	1	0	1	0	0	0
Commercial buildings	31	4	19	1	0	7
Office buildings	1	1	0	0	0	0
Transport and communications buildings	11	0	6	0	0	5
Buildings for institutional care	2	0	1	0	1	0
Assembly buildings	3	0	2	0	0	1
Educational buildings	1	1	0	0	0	0
Industrial buildings	5	0	3	0	1	1
Warehouses	2	0	0	0	0	2
Other buildings	2	0	1	0	0	1

Table 6.5: Typology of heating in Kökar

It is necessary to evaluate the loads due to the new heat pumps. In order to obtain a profile to add to the existing one, we need to know the heat requirements of these buildings. Regarding the school and the other houses which use oil, the KTH University provided the consumption which has been previously reported in Table 5.3. The heat requirements have been calculated, starting from oil consumption, through the following formula:

$$Q_{heat} = \eta_{stove} \cdot \dot{m}_{oil\ gas} \cdot LHV_{oil\ gas} \quad (6.2)$$

The η_{stove} is the efficiency of an oil stove, $\dot{m}_{oil\ gas}$ is the yearly flow of oil gas (l/y), and $LHV_{oil\ gas}$ is its low heating value. For the stoves, an average efficiency has been assumed from libraries. Once the heat requirement was obtained, the electricity needed by the heat pumps to meet this share was estimated as follows:

$$W_{e,HP} = \frac{Q_{heat}}{COP_{ave}} \quad (6.3)$$

The COP_{ave} is the coefficient of performance of the heat pump. A typical average value of air-to-water heat pump for that geographical location has been assumed [51].

The bakery is one of the buildings which use wood and in particular pellet. It is a commercial building, so we can aspect a different requirement compared to a house. The yearly pellet consumption is known and, updating the parameter in formulas 6.2 and 6.3, the electricity requirement has been calculated.

It would be possible to do the same procedure with the firewood heated house because their yearly consumption is known. However, this estimation could be inaccurate because more information would be required. It has been thus decided to assume comparable the heat requirements of the oil heated buildings and the firewood heated buildings. In fact, the majority of them are detached and semi-detached houses, except for some office or commercial buildings. The new requirement has been obtained starting from the electricity requirement of the oil heated buildings with the following proportion:

$$W_{e,wood} = W_{e,oil} \cdot \frac{n° \ of \ wood \ heated \ buildings}{n° \ of \ oil \ heated \ buildings} \quad (6.4)$$

Of course, the numerator does not include the bakery, and the denominator does not include the school.

The next table reports all the parameters adopted for the estimation of the electricity requirement of the new heat pumps, which are shown in Table 6.7.

	Yearly consumption	Stove Efficiency [%]	LHV	COP_{HP} [-]
Gas oil	49 000 l/y	80 %	9.9876 kWh/l	2
Pellet	1500 kg/y	70 %	5.3 kWh/kg	

Table 6.6: Parameters for the estimation of the requirements [51] [52] [53] [54]

Buildings	Heat requirement [MWh/y]	Electricity requirement [MWh/y]
School	199.8	99.9
Oil heated house	191.8	95.9
Bakery	5.57	2.78
Firewood heated house	296.0	148.0
Total	**693**	**346.5**

Table 6.7: Heat requirements and new heat pumps electricity requirements

Once the yearly requirement was obtained, it is necessary to get a profile for the simulation. A constant profile would not be a good approximation because the heat requirement varies based on the season. A way to estimate the heat requirement of a building is the use of the degree days. Heating degree day of a locality is the sum extended to all days (n), in a conventional annual heating period, of the only positive daily differences between the internal temperature (T_0), conventionally set for each country, and the average daily external temperature (T_i) [55]:

$$HDD = \sum_{i=1}^{n} (T_0 - T_i) \quad (6.5)$$

Degree days are useful to estimate the heating demand of a house on a specific site. It has been assumed a proportionality between degree days and heating requirement. Table 6.8 shows the monthly degree days of the Kökar region. These values have been normalised dividing by the total value and then multiplied by the yearly electricity requirement of the heat pumps, which is proportional to the heating one. Lastly, it has been supposed a constant value for all hours of each month dividing the monthly electricity demand by the number of hours in that month.

Once obtained the hourly profile, it has been added to the load due to the current electricity consumption.

Month	HDD	Normalised HDD	Monthly electricity demand [MWh]	Hourly electricity demand [MWh]
January	567	0.171	59.3	0.080
February	445	0.134	46.5	0.069
March	495	0.149	51.7	0.070
April	330	0.100	34.5	0.048
May	190	0.057	19.9	0.027
June	8	0.002	0.8	0.001
July	12	0.004	1.3	0.002
August	6	0.002	0.6	0.001
September	112	0.034	11.7	0.016
October	326	0.098	34.1	0.046
November	390	0.118	40.8	0.057
December	435	0.131	45.5	0.061

Table 6.8: Degree days and demand of electricity for the heat pumps [56]

The total electricity demand is around 3.17 GWh/y higher than scenario 1 (2.8 GWh). It follows that size and costs of the technology increased, as it is shown in the next figure and the following table. The LCOE is 0.343 €/kWh slightly decreased compared to scenario 1 (0.349 €/kWh).

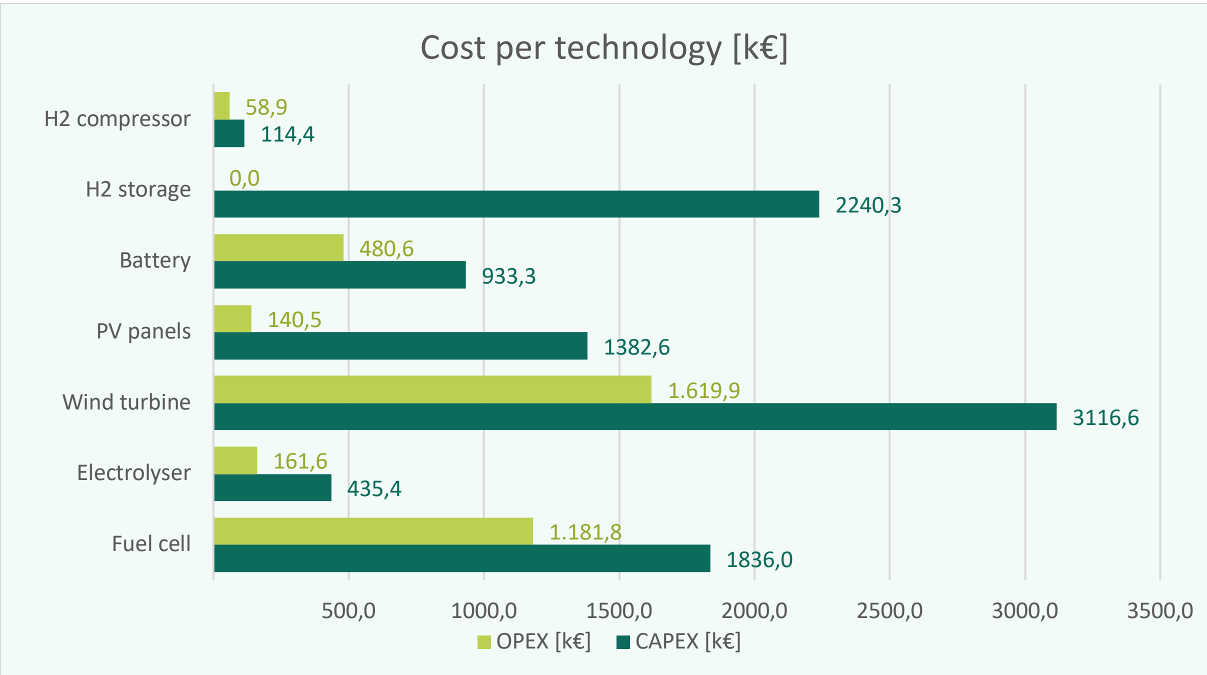

Figure 6.21: CAPEX and OPEX of the nodes (scenario 4)

Node	Capacity	Unit
Fuel cell	359	kW
Electrolyser	319	kW
Wind turbine	2948	kW
PV panels	693	kW
Battery	1700	kWh
H2 storage	5481	kg
H2 compressor	6	kg/h

Table 6.9: Nodes size (scenario 4)

The configuration of the energy flows is similar to scenario 1, with a more important role of the electricity from wind turbines to loads (60 %) at the expense of the batteries (14 %). In fact, the battery node is the only one with a smaller capacity in comparison with the first scenario. There is also a slight increase in curtailments as far as the energy produced by the photovoltaic panels is concerned.

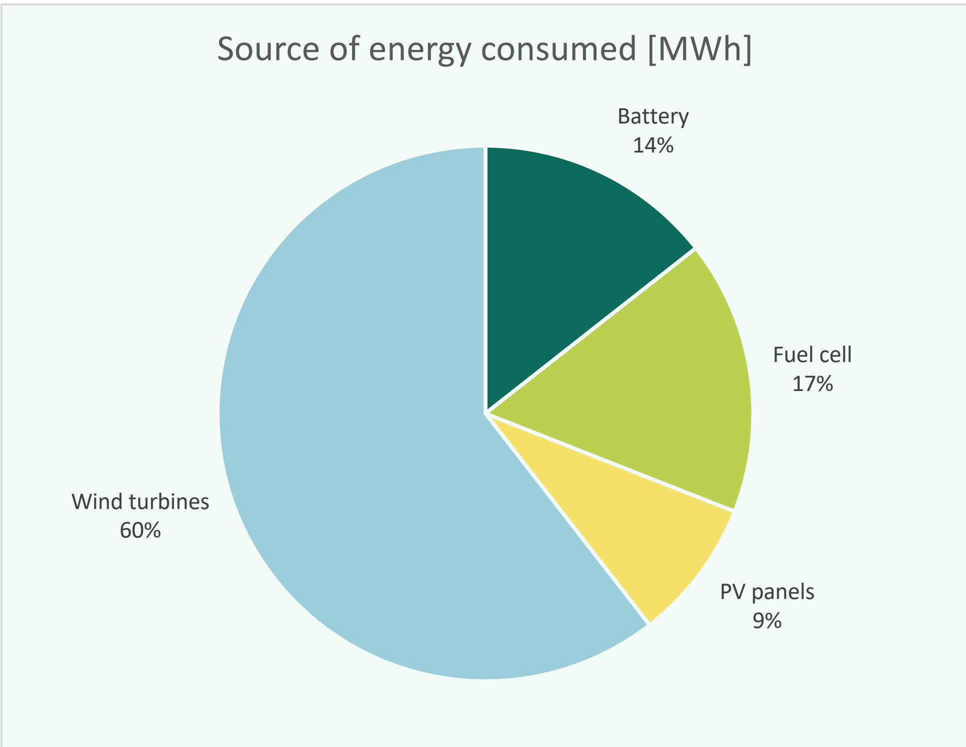

Figure 6.22: Shares of electricity from nodes (scenario 4)

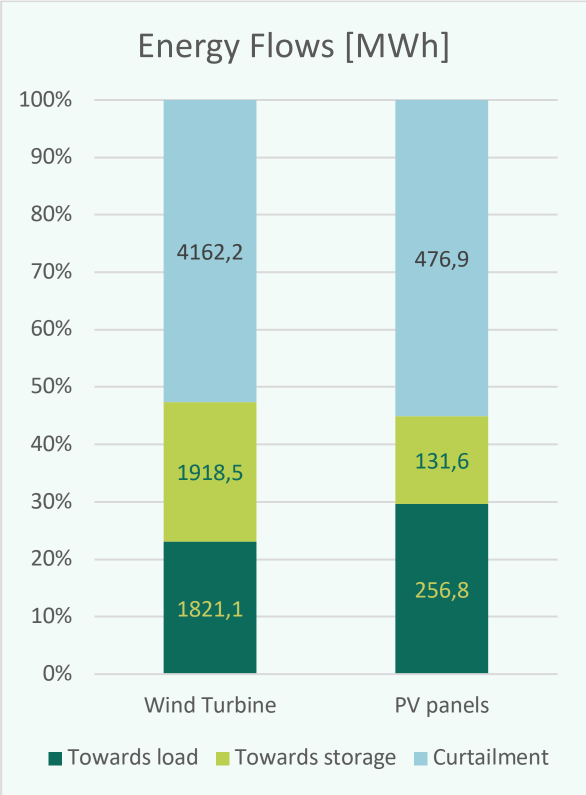

Figure 6.23: Flows of energy from production nodes (scenario 4)

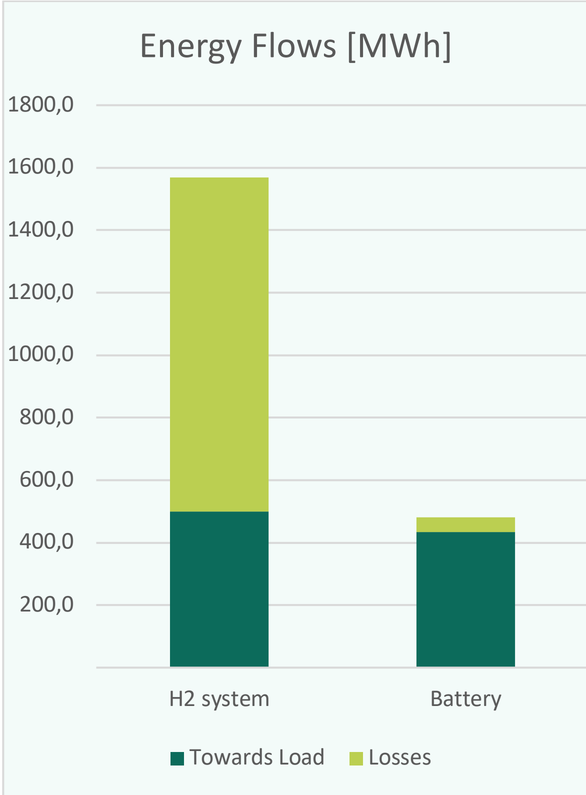

Figure 6.24: Flows of energy from storage nodes (scenario 4)

Lastly, the following panel shows the water consumption, due to the electrolysers, and the other products during all the periods of the analysis.

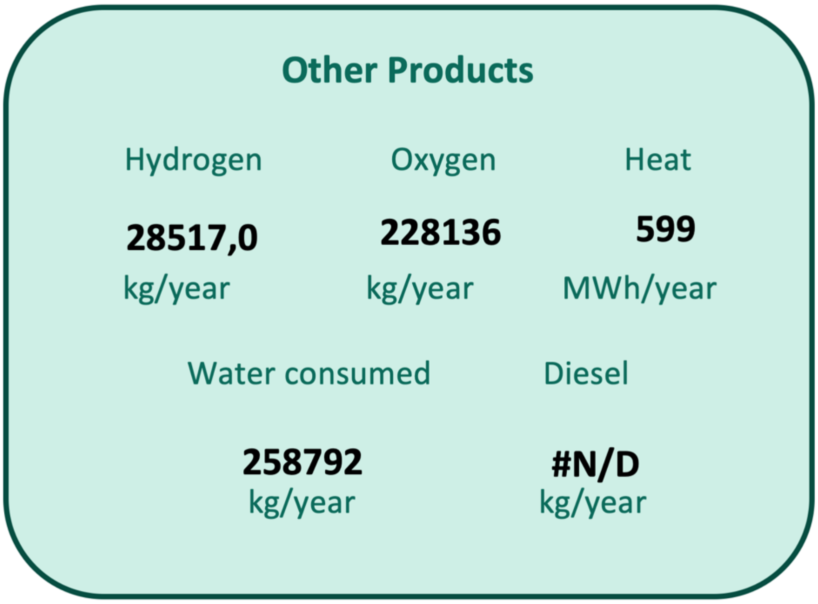

Figure 6.25: Other products and water consumption (scenario 4)

6.5 Scenario 5: total electric loads, electric heating and electric mobility

Figure 6.26: Scenario 5 configuration

This scenario is a combination of scenario 2 and scenario 4. The system should be designed to meet current electrical loads, the electrical load due to electric mobility and the replacement of wood and oil heating systems with heat pumps. The new profile has been obtained by adding these three contributions, and the new total electric requirement is around 4 GWh per year. A substantial increase in demand requires a bigger system. In comparison with scenario 2 (electric mobility), the surplus of demand for the electric heating is met increasing the capacity of the wind turbines (almost 400 kW more) and the hydrogen system, with the storage system which must be capable of containing 1 ton of hydrogen. Next chart reports the costs of the nodes, while Table 6.10 shows their sizes.

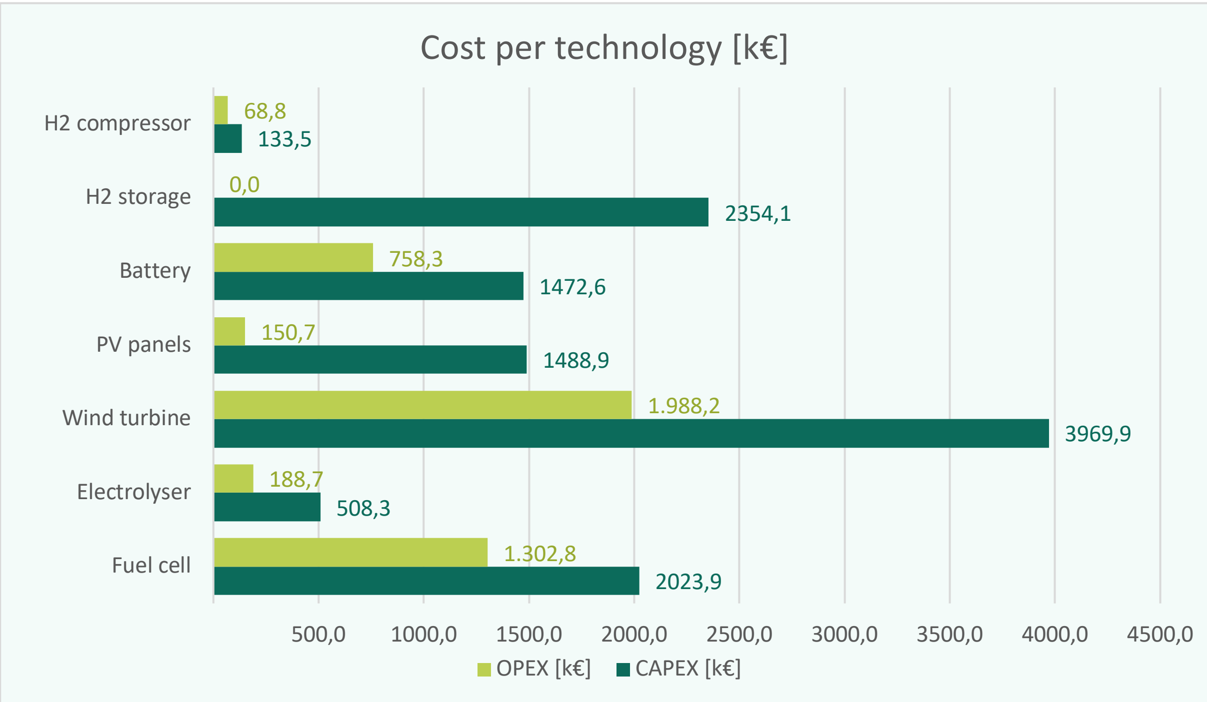

Figure 6.27: CAPEX and OPEX of the nodes (scenario 5)

Node	Capacity	Unit
Fuel cell	396	kW
Electrolyser	372	kW
Wind turbine	3619	kW
PV panels	743	kW
Battery	2682	kWh
H2 storage	5760	kg
H2 compressor	7	kg/h

Table 6.10: Nodes size (scenario 5)

The LCOE is 0.324 €/kWh, and it is slightly decreased compared to scenario 2 (0.328 €/kWh). In fact, it is the lowest value of all analysed so far. The incidence of electricity from wind turbines is higher, while that from batteries (16 %) and directly from photovoltaic panels (7 %) is decreased. Indeed, net of an increase in electricity needs compared to scenario 2, the model decided to install a photovoltaic system and a battery pack with a slightly lower capacity. The share of curtailment does not vary significantly.

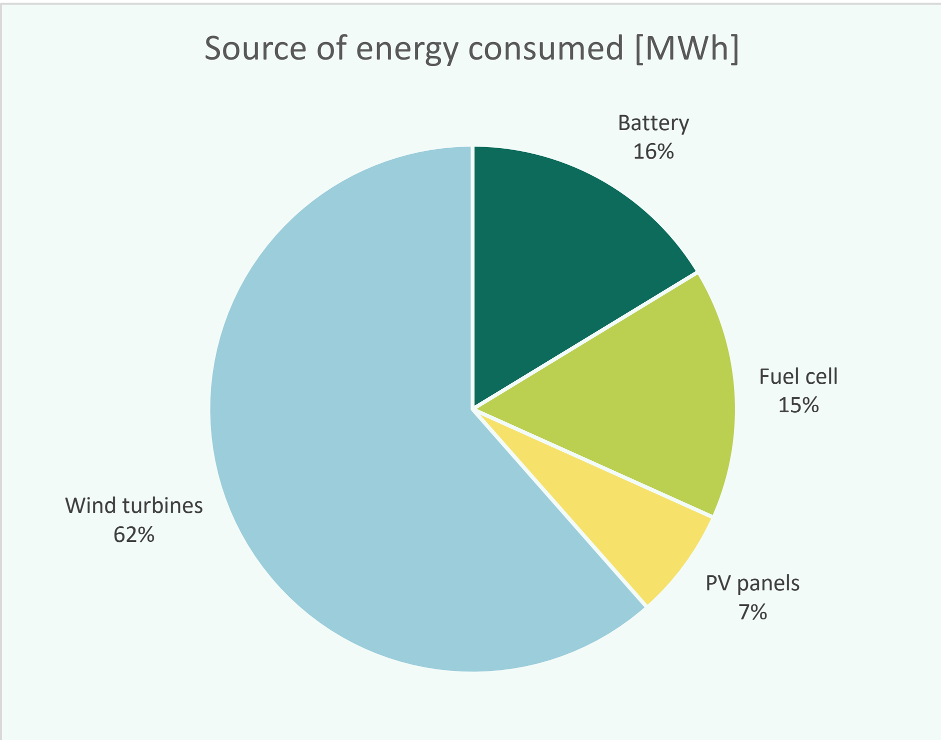

Figure 6.28: Shares of electricity from nodes (scenario 5)

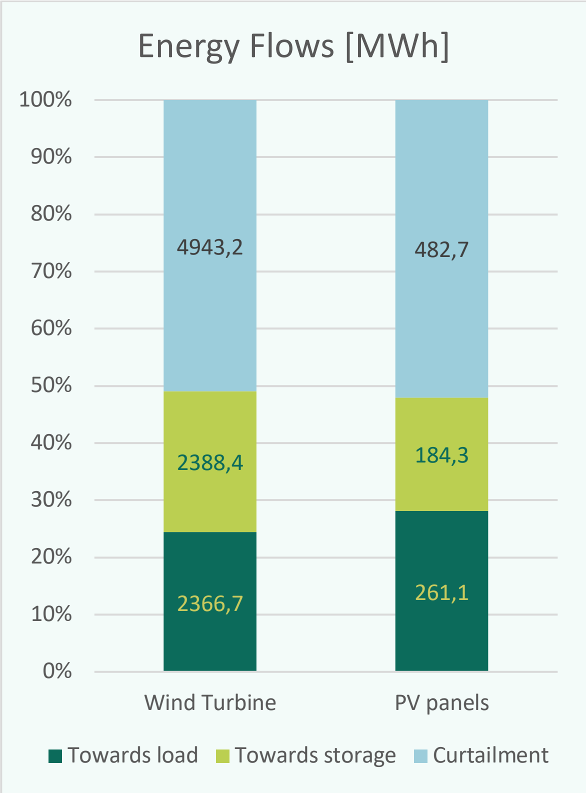

Figure 6.29: Flows of energy from production nodes (scenario 5)

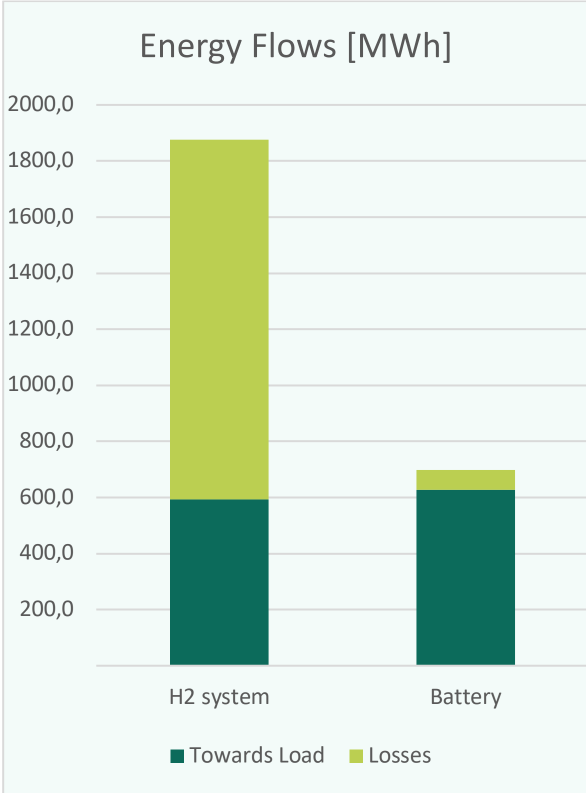

Figure 6.30: Flows of energy from storage nodes (scenario 5)

Next figure shows how all the products and consumption related to the hydrogen system increase, given its greater use and larger size.

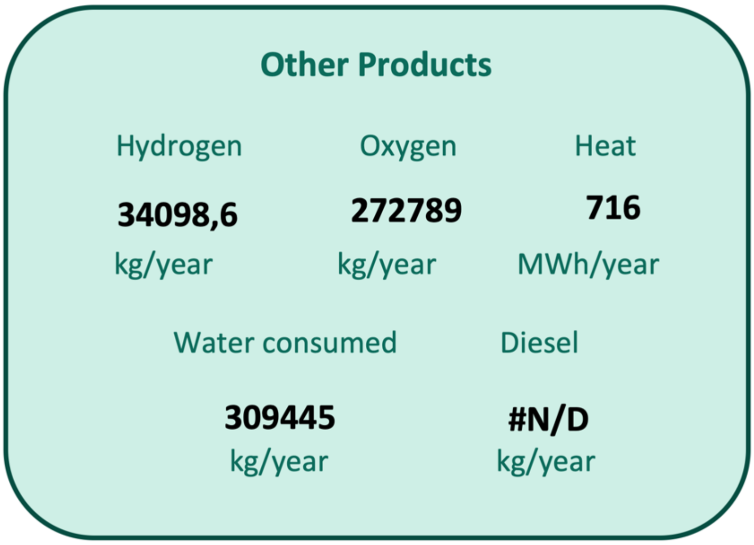

Figure 6.31: Other products and water consumption (scenario 5)

6.6 Scenario 6: total electric loads, electric heating and hydrogen mobility

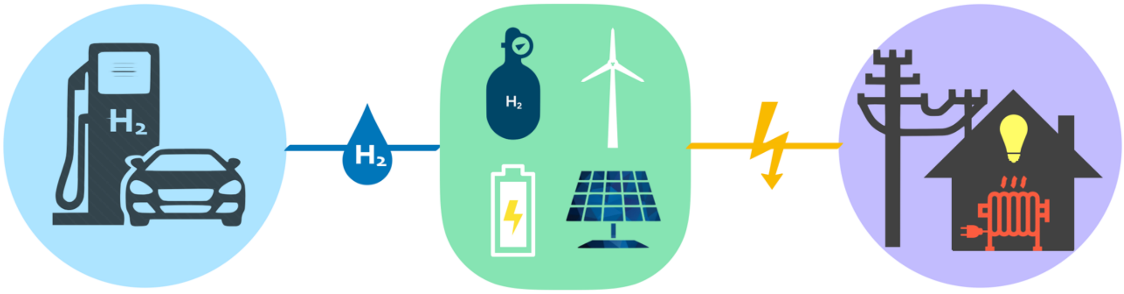

Figure 6.32: Scenario 6 configuration

This scenario is a combination of scenario 3 and scenario 4. The system should be designed to meet current electrical loads, the electrical load due to electric mobility and the hydrogen needs for the mobility. The total electricity demand is 3.17 GWh/y, and the hydrogen demand is equal to 33546 kg/y. To cope with the increase in electricity needs compared to scenario 3 (hydrogen mobility without electric heating), the size of all the hydrogen system wallpapers has increased, as has the capacity of wind turbines. The capacity of the photovoltaic panels does not vary much, while that one of the batteries is lower. Probably the model, for very large quantities of energy, considers it convenient to store it in the form of hydrogen, exploiting the size of the hydrogen tank which is justified by the demand for fuel for vehicles. It follows that the percentage of electricity directly provided by wind turbines slightly increases (59 %) at the expanse of that from batteries. The rest of the shares is almost unchanged in percentage, as we can see in Figure 6.34.

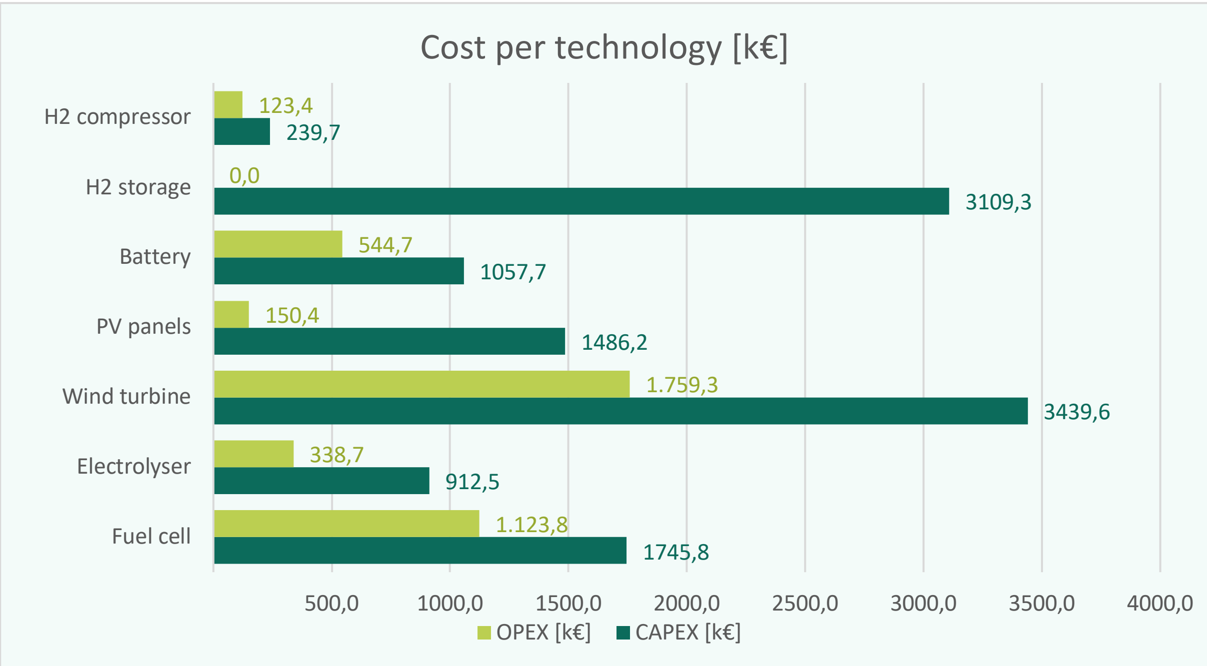

Figure 6.33: CAPEX and OPEX of the nodes (scenario 6)

Node	Capacity	Unit
Fuel cell	342	kW
Electrolyser	668	kW
Wind turbine	3202	kW
PV panels	742	kW
Battery	1926	kWh
H2 storage	7607	kg
H2 compressor	12	kg/h

Table 6.11: Nodes size (scenario 6)

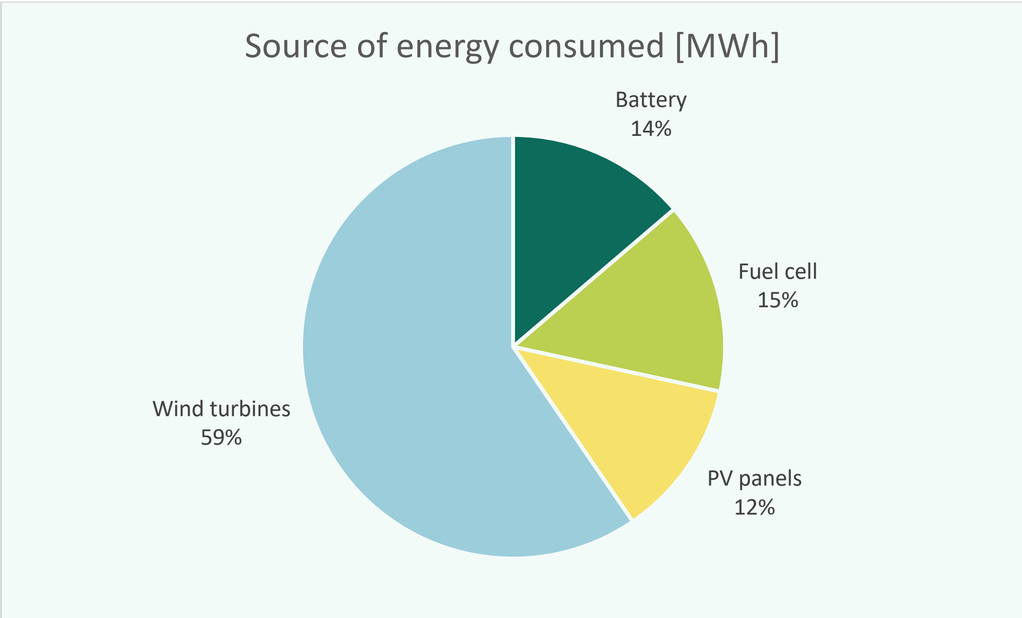

Figure 6.34: Shares of the electricity from nodes (scenario 6)

The new LCOE is equal to 0.406 €/kWh, and it is lower than the third scenario (0.421 €/kWh), but it is higher than that one of scenario 5, as shown previously. However, as previously mentioned, these values are not fully comparable. In fact, although the two systems provide the same services, albeit differently, the scenario 6 plant is not designed solely to produce electricity. This factor affects the fact that the size of the various nodes is optimised to provide electricity and hydrogen for transport simultaneously.

The curtailments are lower (around 40 %) compared to the other scenarios, except for the other scenario with hydrogen mobility which presents a similar situation. In comparison to this last scenario, the amount of electricity directly provided by the photovoltaic panels to the load has risen, with a decreasing of energy passing through the storage and so a better efficiency.

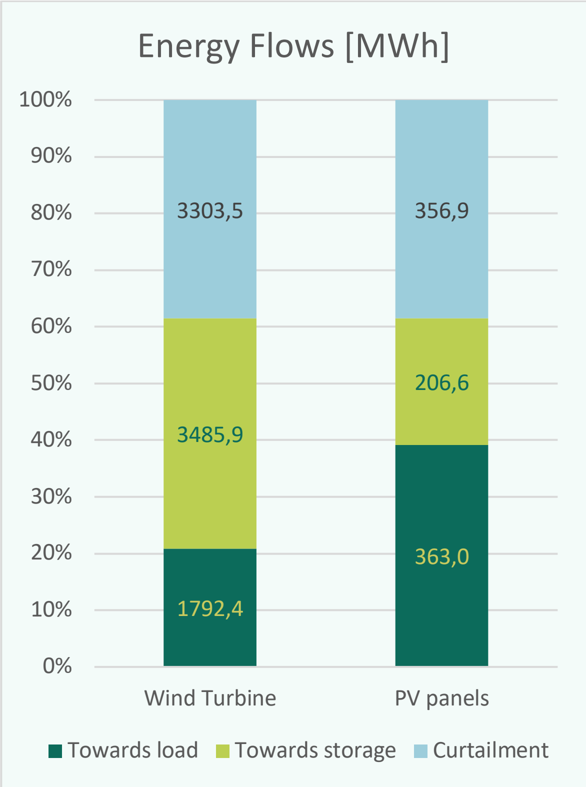

Figure 6.35: Flows of energy from production nodes (scenario 6)

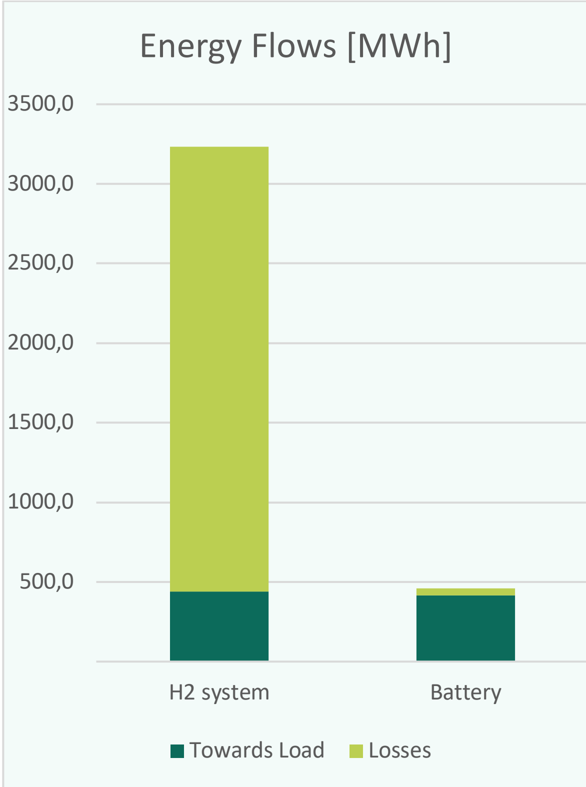

Figure 6.36: Flows of energy from storage nodes (scenario 6)

Next panel shows the production of other products and water consumption. Out of 58777 kg of hydrogen produced, more than 33.5 tons are destined for transport. The $LCOH_2$ of this last quantity is 31.8 €/kg_{H2}. This value is higher than the $LCOH_2$ of scenario 3 (31.8 €/kg_{H2}) as we would expect. In fact, these two plants provide the same amount of hydrogen for the vehicles, but that one of scenario 6 is more expensive because all the equipment for its production has a larger capacity. This is due to the fact that this system must also provide more energy to meet the demand for electricity from the new heat pumps.

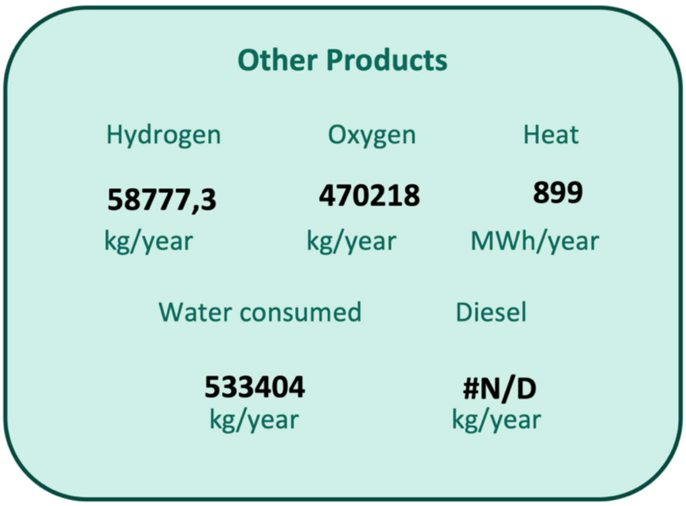

Figure 6.37: Other products and water consumption (scenario 6)

6.7 Comparison and resume of the results

The previous scenarios show as, changing the demands to satisfy, the model elaborates different configuration of the plant. Although the purposes of the various plants are different, we can discuss their economic convenience using the Levelized Cost of Electricity. LCOE gives us an idea of the value of the electricity produced. The previously analysed values are reported in the next figure. Looking at this chart, as we have seen before, the most convenient scenarios would seem to be the fifth, with combine the current electric loads, the electric heating and the electric mobility. In general, we can notice that the LCOE tends to decrease when the electricity load is higher, probably because a rise in the demand allows a more efficient exploiting of the systems. The scenarios with hydrogen mobility deserve to be treated apart for the reasons discussed previously. However, the obtained values are significantly higher than the current electricity price in Finland, taxes included [57].

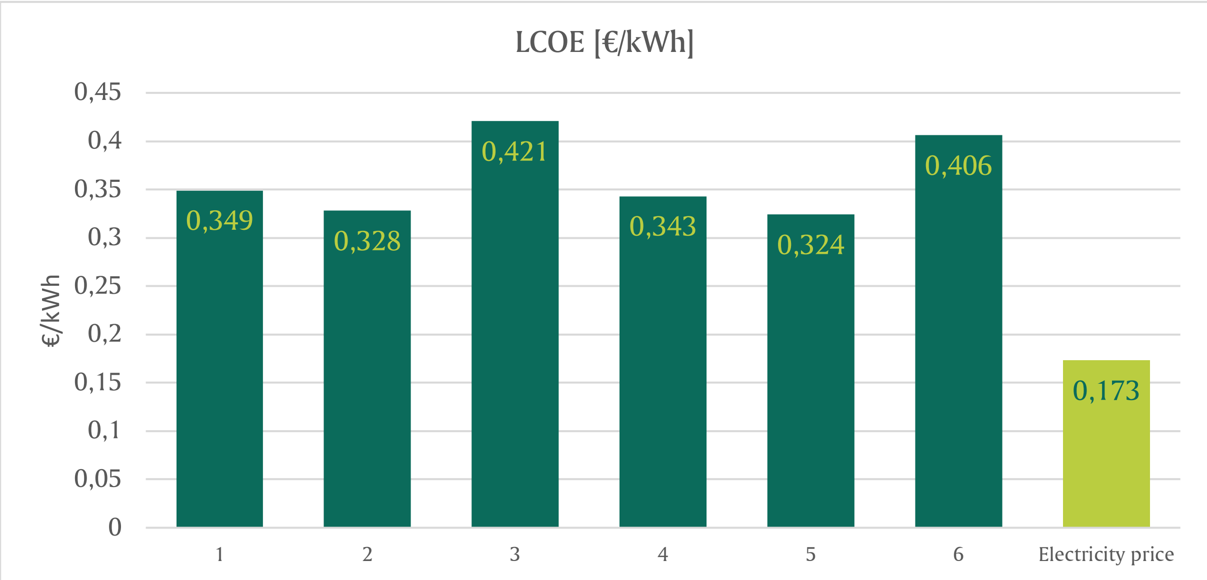

Figure 6.38: LCOE comparison

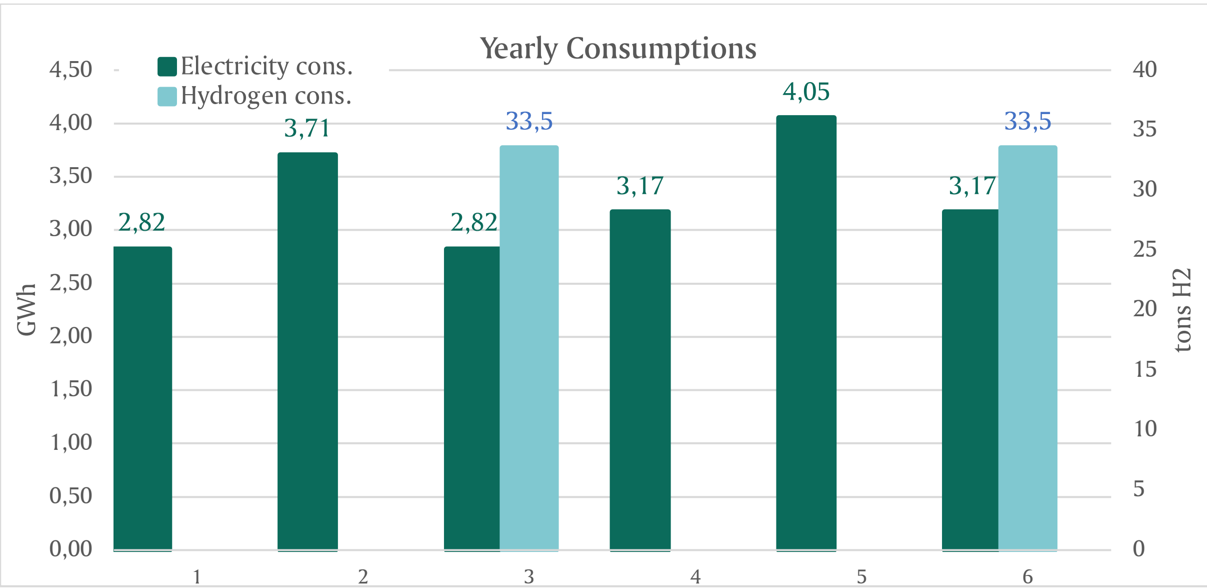

Figure 6.39: Electric and hydrogen consumption

The total plant cost could be a good way to compare the convenience between different scenario. Although the LCOE gives us better information to compare also with different or alternative solutions, we saw that in some case this parameter does not provide proper indication. For example, in scenario 3 or 6, LCOE as calculated does not take into account that the same system is also used to produce hydrogen and that this aspect affects the sizing. For this reason, the total cost can be useful to compare scenarios which provide the same services (electricity, heating, fuel) but in a different way. Using this information, we can notice an important result, which can appear opposite looking only at the LCOE: the total cost of scenario 6 is lower than that of scenario 5, with the same services offered. The same difference is also recorded between scenario 3 and scenario 2. Scenarios with hydrogen vehicles are around € 1 million cheaper than the corresponding with electric vehicles. The reason could be the fact that part of the electricity provided to electric cars was previously converted in hydrogen or stored into the batteries. Its conversion or storage in batteries means that part of the energy is lost in the process. On the other hand, in the case of scenarios with hydrogen mobility, the fuel produced goes directly to the filling stations to then be used by the cars. Although the losses are just shifted to the car's fuel cells, the storage of the electricity into the batteries of the electric cars produces further losses. Other causes could be the distribution of the demand for refuelling in the two different cases. However, these analyses do not take into account the cost of the charging stations for the electric cars or of the hydrogen refuelling station.

Figure 6.40: Total plant cost for different scenarios

Going in particular, in the next picture we can see how total costs are divided (CAPEX and OPEX) in the various scenarios. As already noted for individual cases, the costs of fuel cells and wind turbines are predominant, and together count up to 60 % of the entire plant based on the scenario. The electrolyser takes on greater importance in scenarios 3 and 6 where hydrogen mobility is envisaged, as well as the cost of batteries affects up to about 15% in scenarios with electric mobility. It is important to note how the role of the entire hydrogen system is significant: in some cases, it affects up to 50 % of the total costs of the plant. For example, in case 1 we have seen how the batteries and the hydrogen system provide a comparable share of electricity to the loads. Nevertheless, while batteries represent about 14% of the total cost, all the apparatuses that contribute to the production, storage, and transformation of hydrogen into electricity represent almost 48 %.

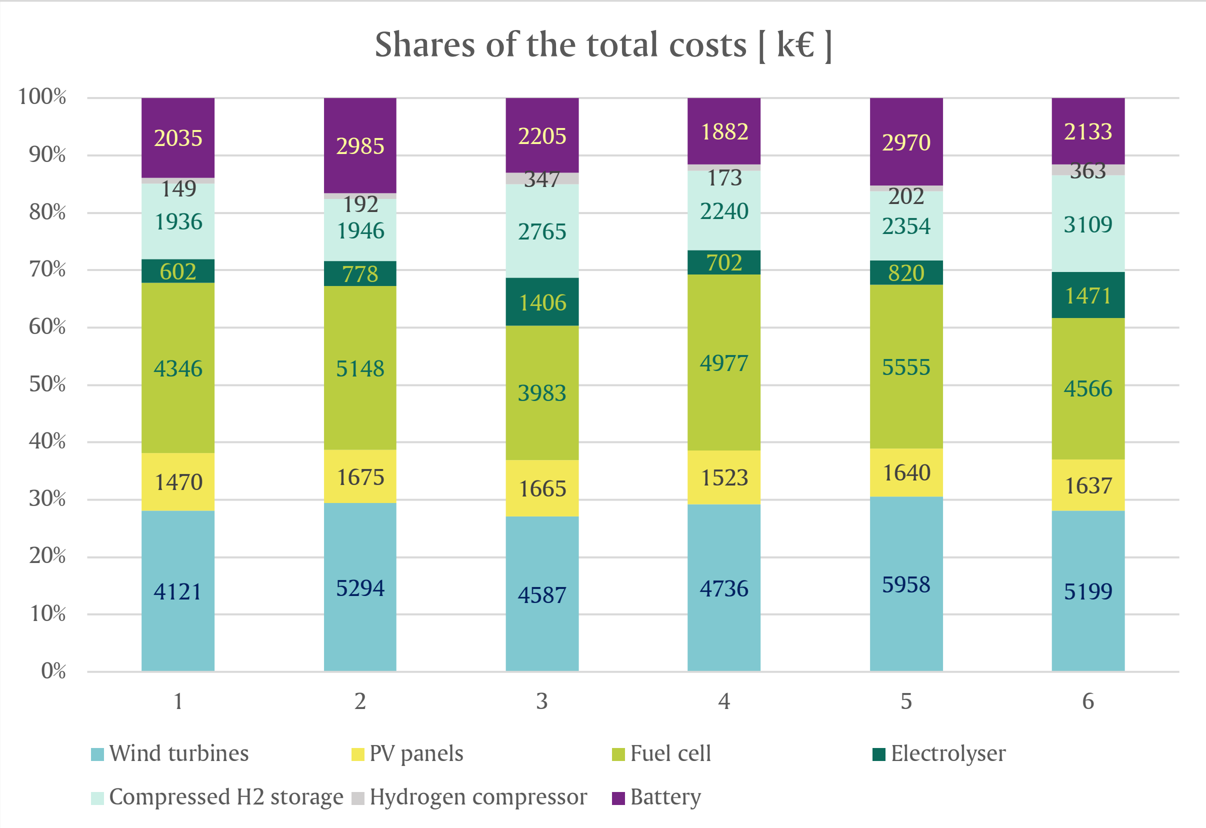

Figure 6.41: Total costs incidence per each scenario

In the next figures, we can see a comparison of the capacities between different scenarios. The first shows the sizes of the production nodes, so wind turbines and photovoltaic panels. The capacity of the wind farm is linked to energy demand. We can notice that, for scenarios 2 and 3 or 5 and 6, the size of the wind farm is smaller where it is chosen to have hydrogen mobility rather than electric. The total capacity of the photovoltaic panels is also affected by the energy demand, but this is not the only parameter. In fact, we can notice that in the cases with electric heating, the model has decided to install a lower capacity of photovoltaic panels compared to the same cases without heating, except for the former. This choice may be due to the distribution of the demand: heating demand is concentrated in periods with few daylight hours, and so the system may decide to meet the higher needs installing more wind turbines capacity.

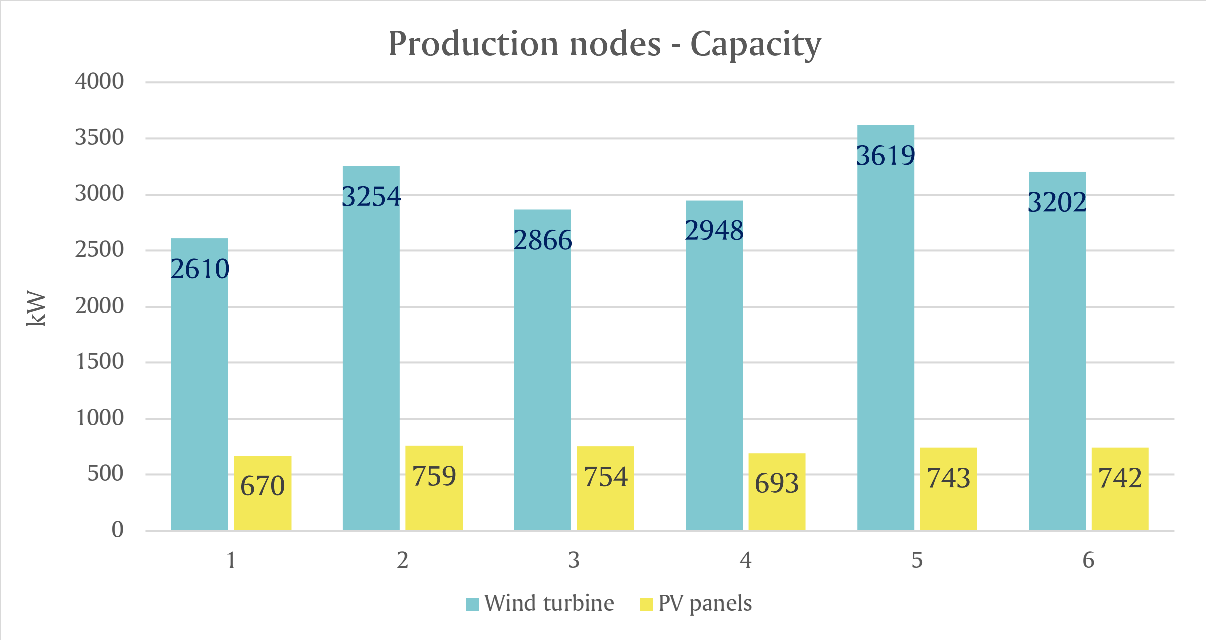

Figure 6.42: Sizes of the production nodes

As regards fuel cell, the capacity is strictly affected by electricity needs. In fact, their role is only that to convert hydrogen into electric power. On the contrary, the electrolyser produces hydrogen both as storage and, in scenarios 3 and 6, as fuel for vehicles. It follows that the capacity of the electrolysers has more than doubled in the cases with hydrogen mobility. The fact that, according to the data used, the electrolyser has a lower unit cost than that of the fuel cells, means that, although increasing its size, this does not affect the total cost of the system excessively. This factor may, therefore, contribute to the previously seen results according to which, in terms of plant costs, the system with hydrogen mobility is more convenient than the system with electric mobility.

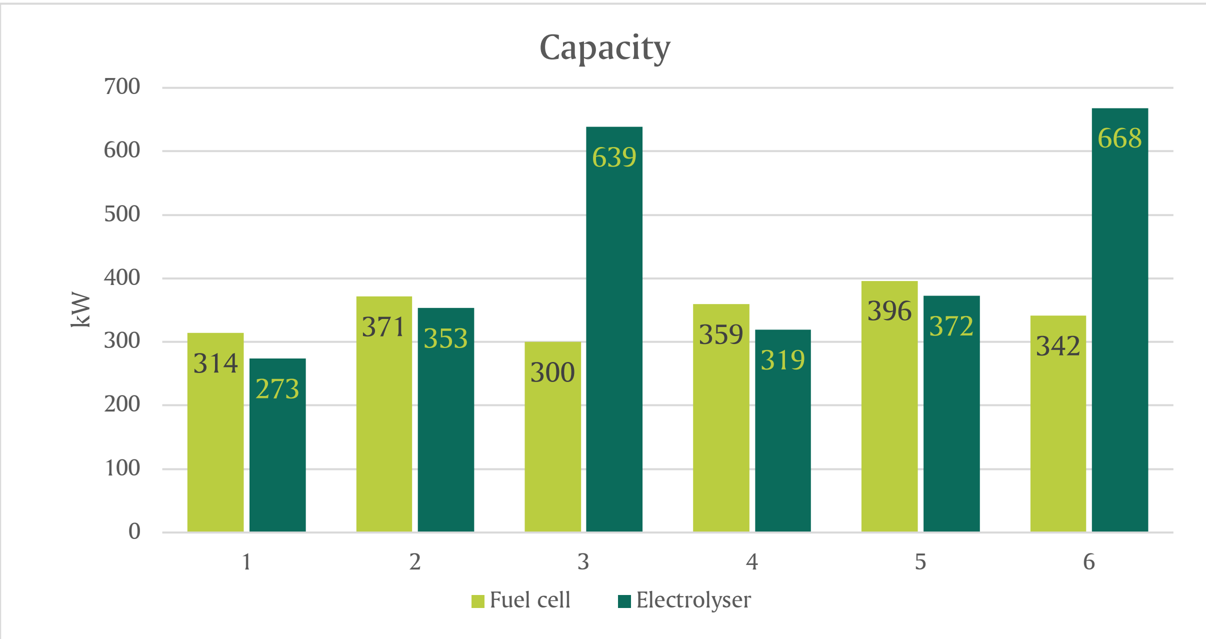

Figure 6.43: Sizes of fuel cells and electrolysers

It has already discussed as, in scenarios which include transportation needs to meet, the addition of heating requirements does not cause an increase of the battery capacity, but instead a slight decrease. On the contrary, there is a significant rise adding electricity needs for electric car rather than for hydrogen storage capacity. In fact, passing from scenario 1 to 2 and from 4 to 5 compared to batteries, the increase of hydrogen storage is less relevant. It becomes much more important in scenarios 3 and 6 where it is necessary to store hydrogen for transport.

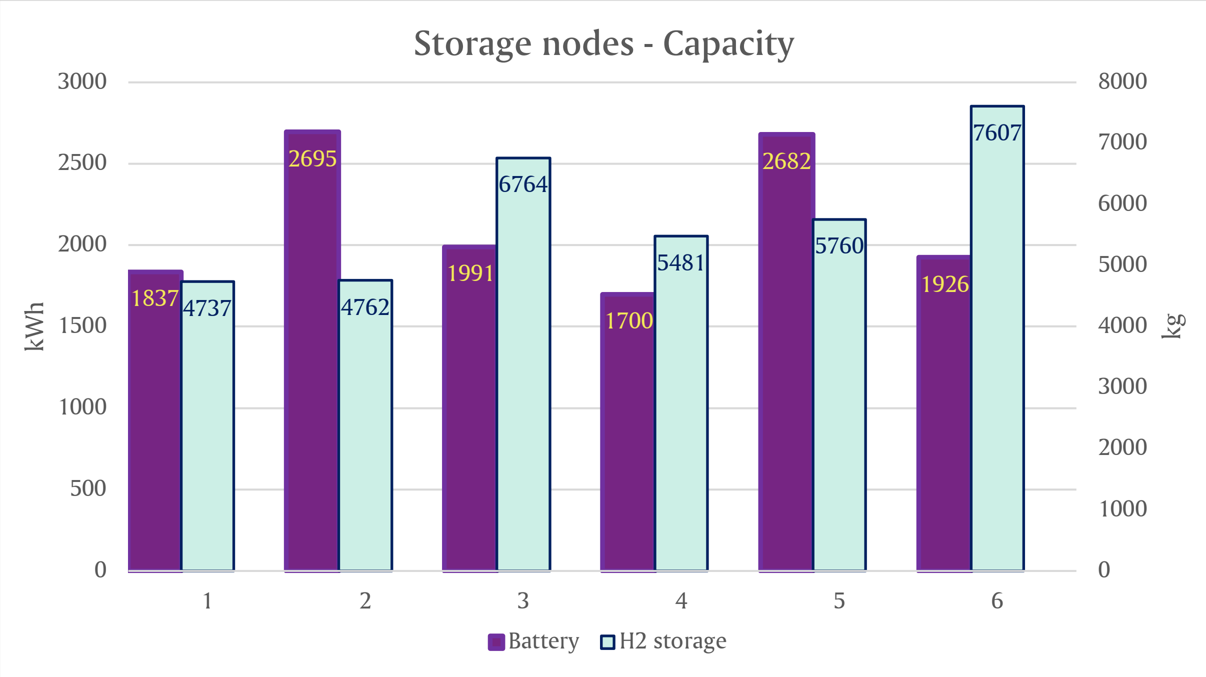

Figure 6.44: Sizes of the storage nodes

Lastly, Figure 6.45 shows the waste heat per year from electrolysers and fuel cells. The amount of heat is huge and, how we can expect, is affected by the size and the operation of the hydrogen system. This heat may have some applications, but it also depends, as we will see in the conclusions, by the temperature of the source. The table below reports the water consumption, which is an important value to consider for the realisation of the system, in particular on an island, and the oxygen and hydrogen production.

Other products and water consumption (Mg/year)

Scenario	Water	Hydrogen	Oxygen
1	231	25	204
2	287	32	253
3	505	56	445
4	259	29	228
5	309	34	273
6	533	59	470

Table 6.12: Products and water consumption for all scenarios

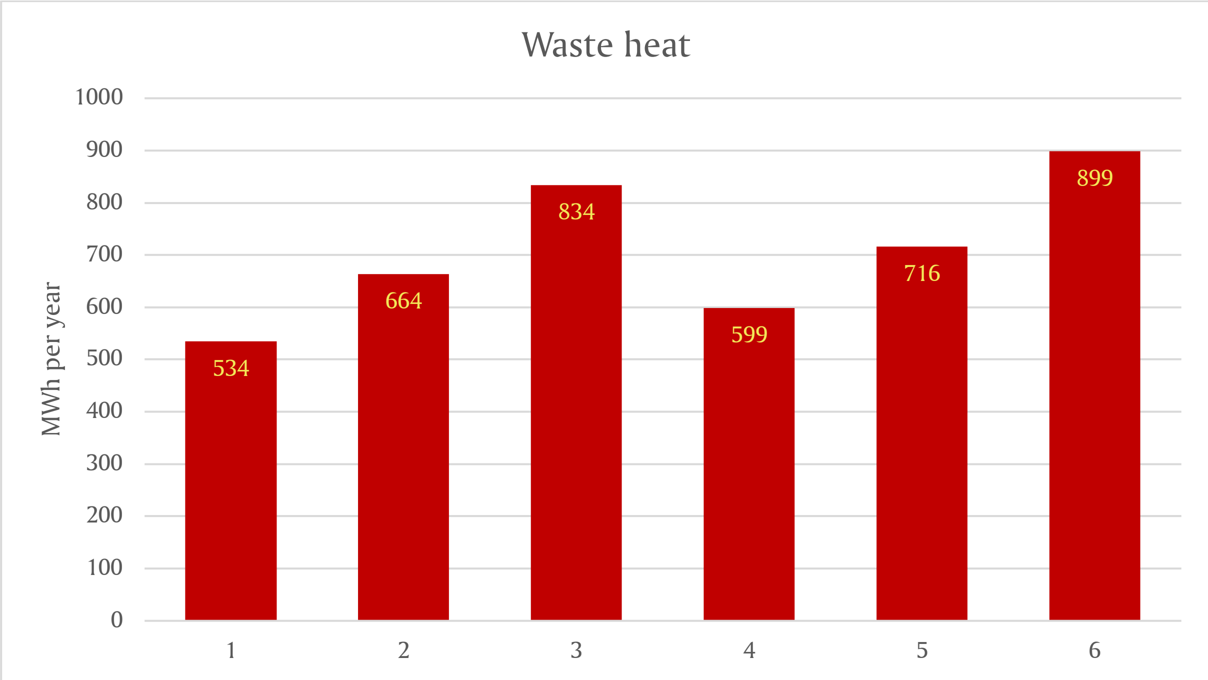

Figure 6.45: Waste heat from electrolysers and fuel cells

7. Conclusions and recommendations

In this Master Thesis work, a publicly available tool to calculate the optimal sizing of hybrid systems for remote application has been developed. This work was carried out during an internship at SINTEF, a Norwegian company which collaborates with Politecnico di Torino and other partners on an EU-funded project called REMOTE. REMOTE aims to demonstrate the technical and economic feasibility of fuel cells-based hydrogen energy storage solutions with installation in either isolated micro-grids or off-grid remote areas.

SINTEF has already developed a model (HyOpt) for the sizing optimisation of these kinds of systems. The model consists of three parts: a code in Mosel language, a database and an Excel interface. The work has been focused on the reorganisation of the interface to make the tool accessible to external users. This Excel file was structured to give the possibility to insert input data which were processed by the code. The results were printed in the same file after the code had run. Therefore, it has been decided to add new sheets on the Excel file intended for the user, while the pre-existing sheets have been hidden.

First of all, indications and recommendations about model utilisation have been added in the first sheet of the file. After that, the input part has been simplified, requiring the essential information for the code execution, but also giving the opportunity to enter more detailed indications as an option. It has also been done a research work to set up tables with indicative values for CAPEX and OPEX of the systems which the user can apply in his analysis if he does not have one. For the same reason, indications have also been given for websites that can provide the hourly profiles required about renewable sources on the selected location.

In the output part, several charts and panels have been added to provide economic and operational information about the simulated system. This configuration has been developed to give a clear and quick view of the most relevant results of the model. In the future, depending on the needs of the company and the use they want to assign to this model, a larger quantity of data could be made accessible, which at the moment are elaborated and shown synthetically in the first sheet of output. The other two sheets report the power profiles and storage levels hour by hour for a whole year, and the user can modify the range to display.

The tool has been validated, applying it to a new case study. The case study regards the island of Kökar, in Finland. Kökar receives electricity through a sea cable and from a wind turbine installed on it, but the service is not stable, and several problems occur during the year. The data about electricity, loads and wind power production have been provided by the KTH University. However, the profiles are incomplete and, for this reason, several assumptions have been necessary. The results are affected by that, and a finer study could be executed with more appropriate information. Using the new tool, we proceeded to the analysis of a system which was totally independent and could supply energy to the island only by using renewable resources. It has been noted as, to meet the current loads, a significant investment is necessary. Plants of considerable capacity should be installed compared to those on the island, also trying to understand if from a logistical point of view this solution is viable. Just think of the wind turbines, which would require a capacity at least five times higher than that currently installed on the island.

The cost of electricity produced, then, would be considerably high, if we compare the LCOE obtained for the base case, equal to 0.349 €/kWh, with the current electricity price in Finland, which stands at around 0.1734 €/kWh taxes included. On the other hand, this solution allows for avoiding the emission of almost 200 ton of $CO_{2,eq}$ per year.

Other scenarios have been analysed, assuming to have new loads to meet, related to mobility and heating. In these scenarios, the conversion of the current system was assessed in order to minimise or cancel local emissions of CO_2 and other pollutants related to the combustion of fossil fuels for various uses. In order to pursue this purpose, it was assumed to have fully electric mobility on the island and to reconvert the current wood or gas oil heating systems with heat pumps which can exploit the electricity produced on-site from renewable sources. Under certain assumptions, the model has produced results that demonstrate how by increasing the loads, despite a greater investment, the LCOE decreases up to a value of 0.324 €/kWh. This value is still larger than the current electricity price, but we should consider that the sea cable installed cannot provide enough electricity to satisfy these new loads since it is already difficult to meet the current demand and its capacity is only 1.5 MW. Therefore, the replacement cost to install new appropriate cables should be considered and compared to the investment cost of this solution, also considering $CO_{2,eq}$ emission.

In the other two scenarios, it has been explored the possibility to adopt hydrogen-based mobility. This solution would exploit the installed system for power production, enlarging them to provide hydrogen as a fuel for the vehicles. In addition to practical advantages, it has been noted as this choice can be cheaper compared to scenarios with electric mobility. In fact, although the LCOE (0.406 €/kWh in the scenario including heating) and the LCOH2 are high, these values do not consider that the size of the plant is affected by its the double aim: providing electricity and hydrogen as fuel. As already mentioned, it could be useful to consider a corrected parameter which takes into account as much the operation of a nodes serves to supplies electricity or to produce hydrogen for the refuelling station. However, looking at the total investment cost, the solution with hydrogen mobility can be more convenient than that with electric mobility, with the same services to satisfy. Net of costs related to facilities and under certain assumptions seen previously, the hydrogen mobility scenario could lead to an investment saving of around € 1 million.

Furthermore, a hydrogen system could have other advantages. It could be speculated to recover the waste heat to use for other purposes, like district heating. The amount of heat delivered from the hydrogen system may be sufficient to meet the heating needs of the Kökar population. In fact, it has been estimated that the requirement for the building using gas oil or wood heating systems is around 693 MWh/y, and in scenario 3 (it makes no sense to consider 6 because full electric heating is included there) the waste heat is 834 MWh/y. The problem is not the amount of heat but its quality. A PEM electrolyser works at low temperature, so the heat is released around 70-80 °C [58], which makes it difficult to use for heating purpose. However, several applications have been in investigated to exploit this waste heat for space or water heating, also in combination with other technology, increasing the efficiency of the fuel cell or the electrolyser [59] [60] [61].

There is also a big amount of oxygen produced from fuel cells and electrolysers, which can represent a source of income. The oxygen is required for several uses (medical, chemical, industrial), and its market is expected to grow of roughly 3.9% over the next four years [62].

Lastly, as regards Kökar case study, it would be possible to exanimate a bigger plant which may provide hydrogen for the ferries too. In the Ålands, ferries are fundamental to ensure transfers between the other islands and to the mainland, as it is typical for remote islands. However, their fuel consumption is significant (almost 2 million litres per year according to data provided by KTH University) and consequently also the CO_2 emissions. It may be appropriate to subdivide the production in different islands, especially in the largest, to provide an equivalent amount of hydrogen. The realisation of hydrogen-powered car ferries is object of various studies [63] [64] [65] [66], also considering hybrid solutions with batteries [67] and using hydrogen from municipal solid waste [68].

8. Appendix

8.1 Tool sheets

8.1.1 Sheet 1: Guidelines

HyOpt is a model which calculate the optimal sizing of hybrid plants based on battery and hydrogen. In the next sheets, you can enter your data and, in the final sheets, you can see results and simulation about your plant.
Please pay attention to the following guidelines and follow them!
Please do not change the name of the Excel file.

Input: User
In this sheet, you will find several tables for each technology. For each table:
- Decide to include it or not in the analysis. Enter 1 to include it, 0 to not include it, alongside the cell "Include" on the top of the table

Include 1   Include 0

- In the penultimate row of each table, you can insert your data about CAPEX and OPEX. Please respect the following guidelines:
  - Do NOT change the unit
  - Put only 1 CAPEX (mandatory), 1 fixed OPEX and 1 variable OPEX (at least one of two).

- In the last row, you can select one of the technologies from the database or your data. Please, select the cell with the button alongside and then push the button. You can choose from the drop-down menu.

LFP
Flooded LA
VRLA
LFP
LTO
NCA
NMC/LMO
New

Input: Advanced Input
This sheet allows to insert advanced data. The compilation of this sheet is NOT MANDATORY. For each technology, you should follow these guidelines:
- "Existing capacity": select "New" if you want to add a value and put it in the "New" row. Otherwise, select "Standard".
- "Binary investment": select "1" if you want to consider a binary investment, so add data about "Capacity block size", "Minimum Capacity", "Maximum Capacity". Otherwise, select "0".
- "Buffer level" (battery and H2 storage): select "New" if you want to add a value and put it in the "New" row. Otherwise, select "Standard".
- Do NOT change the unit

Input: Profiles
In this sheet, you can insert your wind, solar and load data. It is necessary to enter HOURLY data for a full year.
The order of the data must be the same for each table.
- WIND: Enter wind speed in m/s, and the production rate will be automatically calculated. Alternatively, enter the production rate directly in the alongside column. It is possible to change the parameter of the production function.
- SOLAR: Enter solar irradiance in W/m2
- LOAD: enter power load in MW

If you do not have hourly data for wind speed or solar irradiance from your site, please consult the following website:
- https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html
For hourly radiation data (downloadable in CSV). If you do not know the azimuth and slope, you can decide to choose "Optimize slope and azimuth".

- https://www.renewables.ninja/
For hourly production rate of wind turbine (downloadable in CSV). Please, select a Capacity of 1 kW wind to obtain the production rate.

Now you are ready to RUN the code!

Results
In these sheets, you will find all results after running of the code in some charts.
Please, if you change something in the configuration of the (adding o removing nodes), select the chart and then use the button to be sure to see the data that you wish to view.
In the second and third sheets, you can change the range of graphs using the table on top. Please:
- Select your strategic period (1 or 2).
- Select day between 1 to 365. "graf end" must be higher than "graf start".
- Select hour between 0 to 24. Time will be automatically calculated.

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Contact

Figure 8.1: Sheet 1

8.1.2 Sheet 2: Economic input

Include	1													
Node			CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX fixed	Unit	OPEX fixed	Unit	Efficiency	Unit
	Lead-Acid	Flooded LA		€	139,7	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	82 %	%
	Lead-Acid	VRLA		€	249,9	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	80 %	%
	Li-ion	LFP		€	549,1	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	90 %	%
	Li-ion	LTO		€	997,5	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	96 %	%
BATTERY	Li-ion	NCA		€	334,4	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	95 %	%
	Li-ion	NMC/LMO		€	399	€/kWh	4,0 %	% of CAPEX		€/year		€/kWh y	95 %	%
	Insert your data	New		€	0	€/kWh		% of CAPEX	0	€/year		€/kWh y	90 %	%
	Selected Battery	LFP	0	€	549,1	€/kWh	4 %	% of CAPEX	0	€/year	0	€/kWh y	90 %	%

Include	1											
	Node		CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX fixed	Unit	OPEX fixed	Unit
	Electrolyser	Alkaline		€	766,35	€/kW	3 %	% of CAPEX		€/kW y		€/year
	Electrolyser	PEM		€	1226,16	€/kW	3 %	% of CAPEX		€/kW y		€/year
	Insert your data	New	394477,32	€	1183,431953	€/kW	5 %	% of CAPEX		€/kW y		€/year
	Selected Electrolyser	New	394477,32	€	1183,431953	€/kW	5 %	% of CAPEX	0	€/kW y	0	€/year
			CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX fixed	Unit	OPEX fixed	Unit
	Fuel Cell	FC		€	5109	€/kW	5 %	% of CAPEX		€/kW y		€/year
HYDROGEN	Insert your data	New		€	2583,82643	€/kW		% of CAPEX		€/kW y	2869,8225	€/year
	Selected Fuel Cell	New	0	€	2583,82643	€/kW	0 %	% of CAPEX	0,0	€/kW y	2869,8225	€/year
			CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX fixed	Unit	OPEX fixed	Unit
	Compressed H2 storag	CGH2		€	408,72	€/kg		% of CAPEX		€/kg y		€/year
	Insert your data	New		€	99,58589744	€/kg	3 %	% of CAPEX		€/kg y		€/year
	Selected storage	New	0	€	99,58589744	€/kg	3 %	% of CAPEX	0	€/kg y	0	€/year
	Hydrogen Compresso	Compressor		€	19724	€/kg/h	4 %	% of CAPEX		€/kg/h		€/year
	Insert your data	New		€	100	€/kg/h	3 %	% of CAPEX		€/kg/h		€/year
	Selected compressor	New	0	€	100	€/kg/h	3 %	% of CAPEX	0	€/kg/h	0	€/year

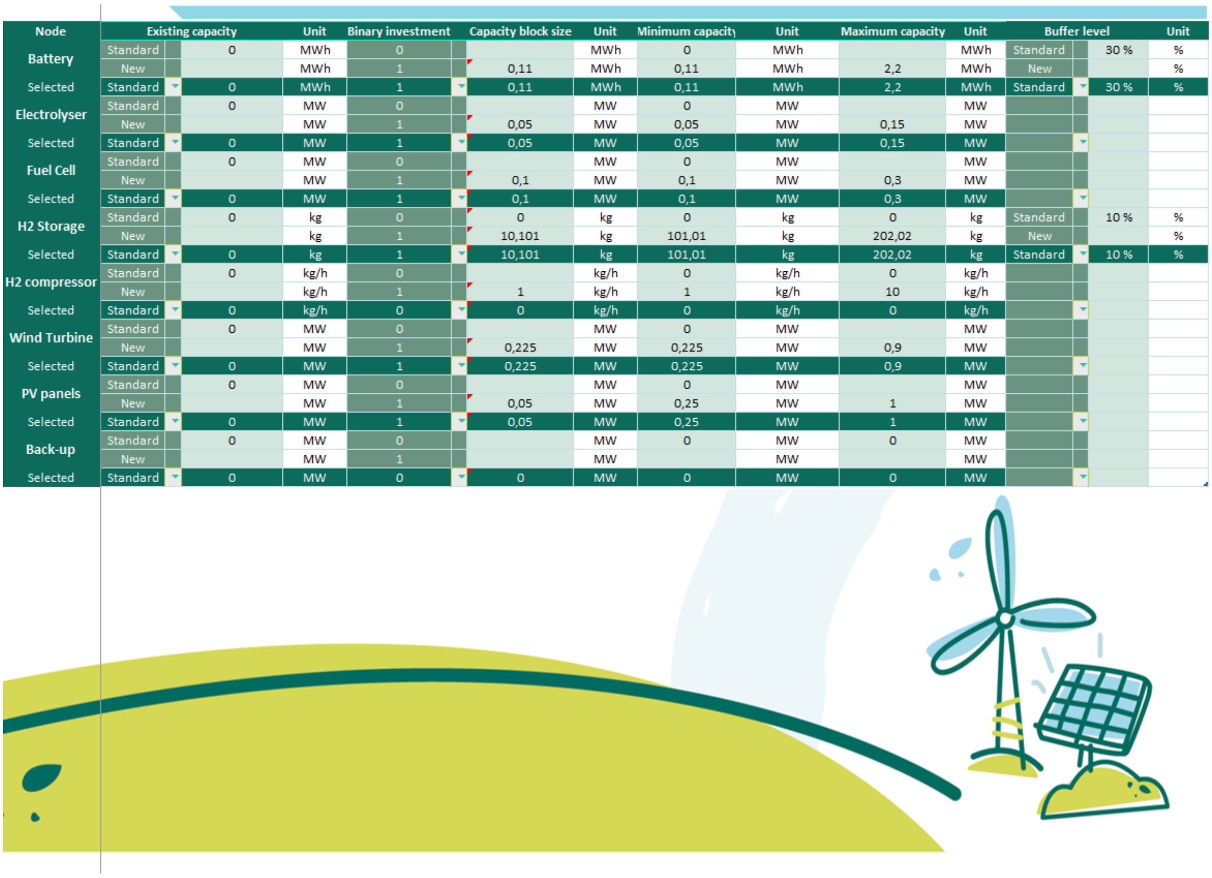
Include	1											
	Node		CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX	Unit	OPEX fixed	Unit
	WT	Onshore		€	1273	€/kW		% of CAPEX	42,68	€/kW y		€/year
WIND TURBINE	WT	Offshore		€	3700	€/kW		% of CAPEX	139,68	€/kW y		€/year
	Insert your data	New		€	1000	€/kW		% of CAPEX		€/kW y	11834,32	€/year
	Selected WT	New	0	€	1000	€/kW	0 %	% of CAPEX	0	€/kW y	11834,32	€/year

Include	1													
	Node		CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX	Unit	OPEX	Unit	OPEX fixed	Unit	Max capacity	Unit
	Solar PV	ooftop residential		€	2587,5	€/kW		% of CAPEX	17,55	€/kW y		€/year	0,005	MW
	Solar PV	Rooftop-C&I		€	2115	€/kW		% of CAPEX	15,8	€/kW y		€/year	1	MW
SOLAR	Solar PV	Community		€	1755	€/kW		% of CAPEX	12,6	€/kW y		€/year	5	MW
	Solar PV	Utility scale		€	900	€/kW		% of CAPEX	9,5	€/kW y		€/year	100	MW
	Insert your data	New		€	2074,95069	€/kW	3 %	% of CAPEX		€/kW y		€/year		MW
	Selected PV	New	0	€	2074,95069	€/kW	3 %	% of CAPEX	0	€/kW y	0	€/year	0	MW

Include	0													
	Node		CAPEX Fixed	Unit	CAPEX variable	Unit	OPEX fuel	Unit	OPEX	Unit	OPEX fix	Unit	OPEX fixed	Unit
BACK-UP	Diesel generator	Diesel generator		€	630,5	€/kW	1,6	€/l		% of CAPEX		€/year	9,7	€/kW y
GENERATOR	Insert your data	New		€		€/kW	1,7	€/kg		% of CAPEX		€/year		€/kW y
	Selected PV	Diesel generator	0	€	630,5	€/kW	1,891	€/kg	0 %	% of CAPEX	0	€/year	9,7	€/kW y

Figure 8.2: Sheet 2

8.1.3 Sheet 3: Advanced input



Node	Existing capacity		Unit	Binary investment	Capacity block size	Unit	Minimum capacity	Unit	Maximum capacity	Unit	Buffer level		Unit
Battery	Standard	0	MWh	0		MWh	0	MWh		MWh	Standard	30 %	%
	New		MWh	1	0,11	MWh	0,11	MWh	2,2	MWh	New		%
Selected	Standard	0	MWh	1	0,11	MWh	0,11	MWh	2,2	MWh	Standard	30 %	%
Electrolyser	Standard	0	MW	0		MW	0	MW		MW			
	New		MW	1	0,05	MW	0,05	MW	0,15	MW			
Selected	Standard	0	MW	1	0,05	MW	0,05	MW	0,15	MW			
Fuel Cell	Standard	0	MW	0		MW	0	MW		MW			
	New		MW	1	0,1	MW	0,1	MW	0,3	MW			
Selected	Standard	0	MW	1	0,1	MW	0,1	MW	0,3	MW			
H2 Storage	Standard	0	kg	0	0	kg	0	kg	0	kg	Standard	10 %	%
	New		kg	1	10,101	kg	101,01	kg	202,02	kg	New		%
Selected	Standard	0	kg	1	10,101	kg	101,01	kg	202,02	kg	Standard	10 %	%
H2 compressor	Standard	0	kg/h	0		kg/h	0	kg/h	0	kg/h			
	New		kg/h	1	1	kg/h	1	kg/h	10	kg/h			
Selected	Standard	0	kg/h	0	0	kg/h	0	kg/h	0	kg/h			
Wind Turbine	Standard	0	MW	0		MW	0	MW		MW			
	New		MW	1	0,225	MW	0,225	MW	0,9	MW			
Selected	Standard	0	MW	1	0,225	MW	0,225	MW	0,9	MW			
PV panels	Standard	0	MW	0		MW	0	MW		MW			
	New		MW	1	0,05	MW	0,25	MW	1	MW			
Selected	Standard	0	MW	1	0,05	MW	0,25	MW	1	MW			
Back-up	Standard	0	MW	0		MW	0	MW	0	MW			
	New		MW	1		MW		MW		MW			
Selected	Standard	0	MW	0	0	MW	0	MW	0	MW			

Figure 8.3: Sheet 3

8.1.4 Sheet 4: Profiles

Wind data					Solar data		Load data	
Data			Production function					
Hour	Wind speed	Production rate	Threshold	Wind speed	Hour	PV panels; irradiance	Hour	Power load
h	m/s	kW/kW installed		kW	h	W/m2	h	MW
1	3,9618	0,2968	Cut-in	4	1	0,0	1	0,047964
2	3,7613	0,2968	Rated	12	2	0,0	2	0,047964
3	3,5609	0,2968	Cut-off	25	3	0,0	3	0,047964
4	3,3604	0,0376	Order	1	4	0,2	4	0,046585553
5	3,1600	0,0119			5	1,8	5	0,045713667
6	2,9595	0,0000			6	3,9	6	0,043335667
7	2,7591	0,0299			7	11,5	7	0,042931
8	3,3437	0,0248			8	20,4	8	0,049336212
9	3,9284	0,0715			9	38,6	9	0,049423167
10	4,5130	0,0677			10	54,6	10	0,047562667
11	5,0977	0,1101			11	95,0	11	0,051211333
12	5,6823	0,1419			12	126,8	12	0,055492667
13	6,2669	0,0952			13	108,3	13	0,043307276
14	6,9675	0,1503			14	82,7	14	0,06371465
15	7,6682	0,1840			15	69,9	15	0,056389
16	8,3688	0,1587			16	50,9	16	0,049500667
17	9,0694	0,1151			17	42,1	17	0,047862
18	9,7700	0,2385			18	23,3	18	0,055013
19	10,4706	0,1201			19	40,0	19	0,052623
20	9,8894	0,1101			20	31,2	20	0,053913
21	9,3083	0,0602			21	22,5	21	0,056603
22	8,7272	0,0489			22	5,5	22	0,052468333
23	8,1461	0,0564			23	1,7	23	0,059458333
24	7,5649	0,0602			24	0,2	24	0,0621
25	6,9838	0,0119			25	0,0	25	0,053954667
26	6,8476	0,0196			26	0,0	26	0,056888
27	6,7114	0,0145			27	0,0	27	0,052058667
28	6,5753	0,0000			28	0,3	28	0,050182667
29	6,4391	0,0000			29	3,2	29	0,051219667
30	6,3029	0,0000			30	8,5	30	0,049263

Figure 8.4: Sheet 4

8.1.5 Sheet 5: User Results

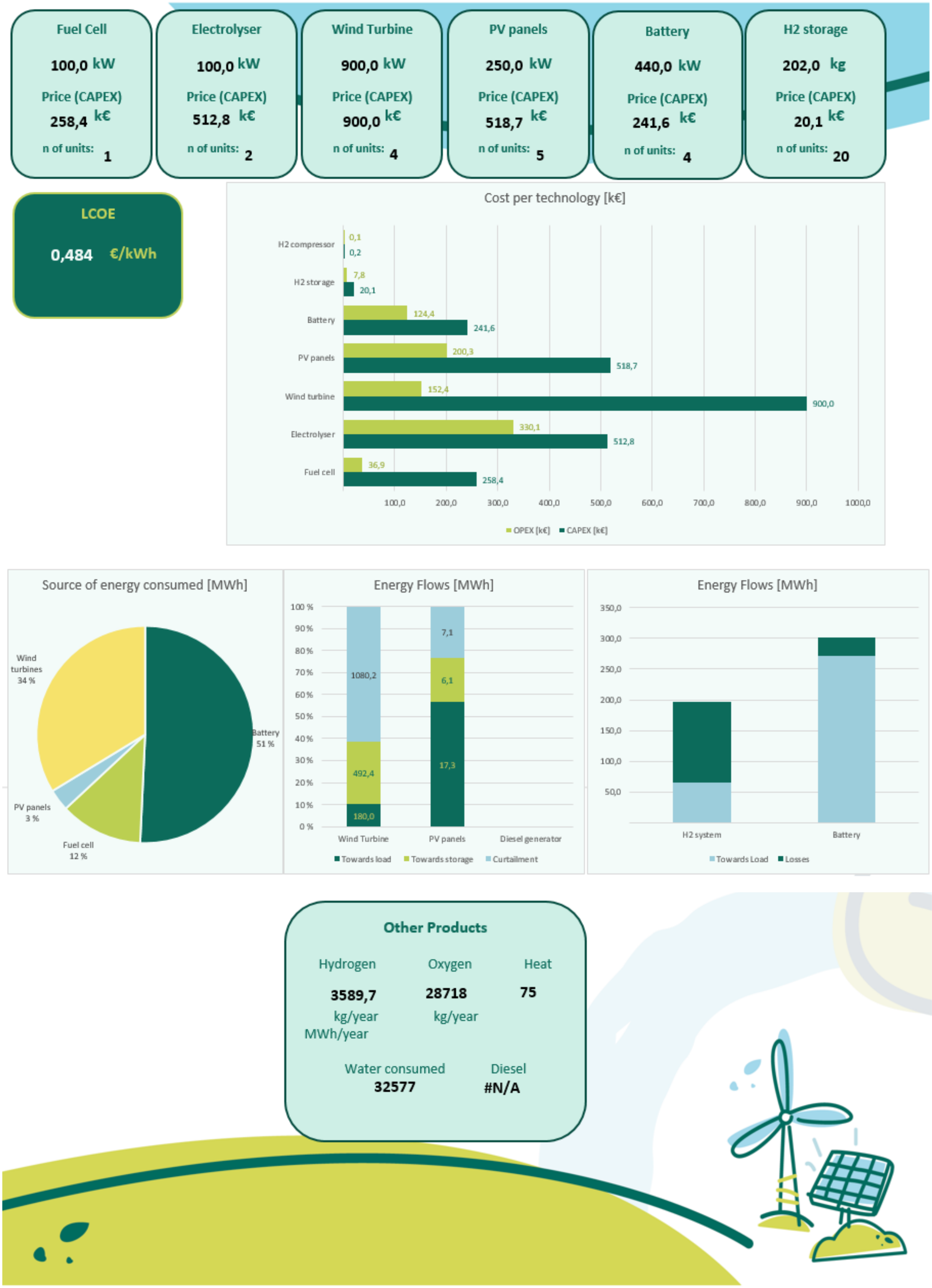


Figure 8.5: Sheet 5

8.1.6 Sheet 6: ResStorage

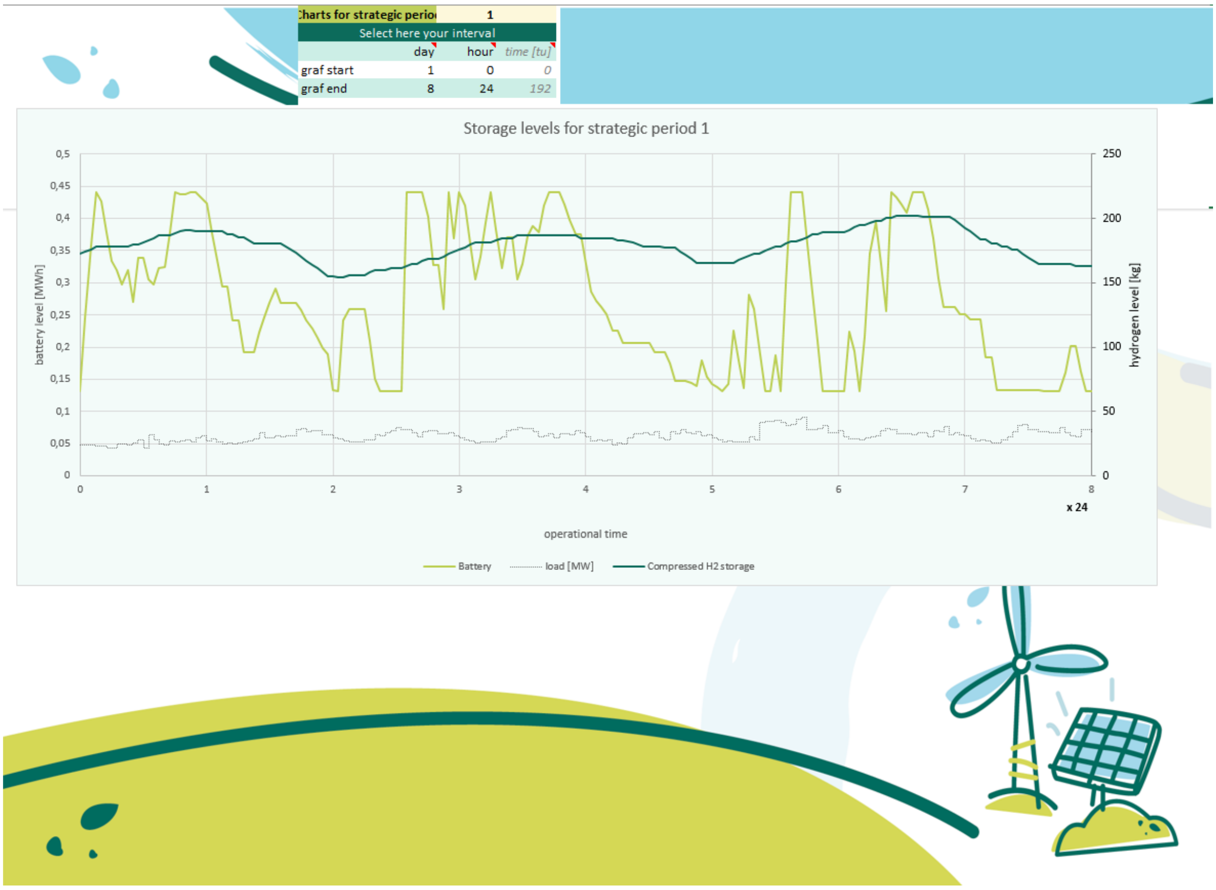


Figure 8.6: Sheet 6

8.1.7 Sheet 7: ResPowerLoad

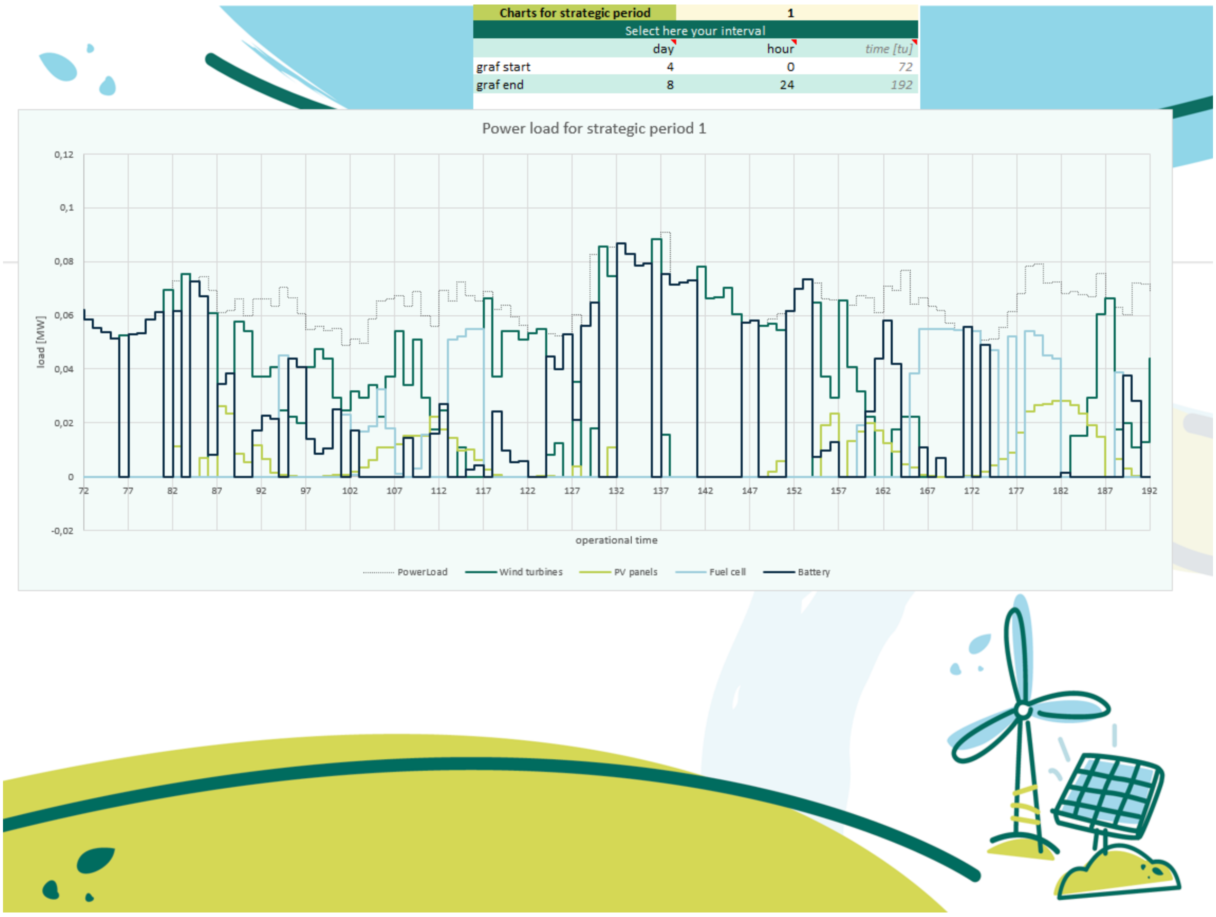


Figure 8.7: Sheet 7

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