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Hydrogen based polygeneration for energy communities.

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Nomenclature and acronyms

ARERA	Regulation Authoriry for Energy, Networks and Environment	AC	Alternating current
CCHP	Combined Cooling Heat and Power	AEMEC	Anion Exchange Membrane Electrolyser Cell
CHP	Combined Heat and Power	AFC	Alkalyne FC
DHW	Domestic Hot Water	DC	Direct current
EE	Electrical energy	DMFC	Direct Methanol FC
GSE	Energy Services Manager	DOD	Depth-of-Discharge
HHV	Higher Heating Value	EC	Electrolyser Cell
H-ICE	Hydrogen fuelled ICE	FC	Fuel Cell
ICE	Internal combustion engine based electro-generator	GHG	GreenHouse Gas
LHV	Lower Heating Value	H-FC	Hydrogen fuelled FC
LPG	Liquid Propane Gas	MCFC	Molten Carbonate FC
PSH	Peak Sun Hours	MEA	Membrane Electrode Assembly
PV	Photo-Voltaic	MH	Metal Hydrides
RES	Renewable Energy Sources	OCV	Open Circuit Voltage
SMES	Small and medium-sized enterprises	PAFC	Phosphoric Acid FC
SWH	Solar Water Heating	PBT	Pay Back Time
TE	Thermal energy	PCM	Phase Change Material
TES	Thermal Energy Storage	PEMFC	Polymer Electrolyte Membrane FC
E_{Sun}	Solar energy	SOC	State of Charge
$E_{PV,e}$	Produced EE by the PV	SOFC	Solid-Oxide Fuel Cell
$E_{PV,e,a}$	Average daily produced EE by PV on annual base	$\eta_{cogeneration}$	Cogeneration efficiency
$E_{EC,ch}$	Chemical energy by EC	E_{out}	Output of electrical energy
$E_{EC,th}$	Thermal energy by EC	E_{in}	Input of electrical energy
$E_{FC/ICE,e}$	Electrical energy by FC/ICE	Q_{out}	Output of thermal energy

$E_{FC/ICE,th}$	Thermal energy by FC/ICE	η_e	Electrical efficiency
$\eta_{FC,e}$	FC electrical efficiency	η_{th}	Thermal efficiency
$\eta_{FC,th}$	FC thermal efficiency	$\eta_{EC,e}$	EC electrical efficiency
$\eta_{ICE,e}$	ICE electrical efficiency	$\eta_{EC,th}$	EC thermal efficiency
$\eta_{ICE,th}$	ICE thermal efficiency	$P_{EC,e}$	EC nominal electrical power consumption
E_{SWH}	Thermal energy by SWH plant	E_{th}	Required TE by the users
E_e	Required EE by the users	$E_{e,d}$	Required EE by the users during the day
$E_{d,d}$	Deficit EE during the day	$E_{e,d,a}$	Average daily required EE by the users during the day
$E_{i,g}$	Imported EE by the grid	$E_{e,n}$	Required EE by the users during the night
$E_{ss,r}$	Reserve of stored EE	$E_{e,g}$	Exported EE to the grid
S_b	Battery size	E_s	Storable EE during the day
N_e	Number of EC modules	E_{ss}	Storable EE by the storage system
$E_{ss,out}$	Outcoming EE by the storage system	$E_{ss,max}$	Maximum storable EE by the storage system
E_{a-b}	TE by the auxiliary boiler	η_{ss}	Storage system efficiency
E_{s-u}	EE supplied to the users	SS	Electrical self-suffiency
E_g	EE exchanged with the grid	SS_{oa}	Overall self-suffiency
E_c	Recovered TE by the cogeneration system	η_{oa}	Overall efficiency

1. Introduction

Currently, the climate changes and their impacts are one of the most important international problems. The current changes in our planet's climate are redrawing the world and magnifying the risks for instability in all forms. The last two decades included 18 of the warmest years on record. The impact of global warming is transforming our environment, increasing the frequency and intensity of extreme weather events.

The Intergovernmental Panel on Climate Change (IPCC) issued in October 2018 its Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas (GHG) emission pathways [1]. Based on scientific evidence, this demonstrates that human-induced global warming has already reached 1°C above preindustrial levels and is increasing at approximately 0.2°C per decade. Without stepping up international climate action, global average temperature increase could reach 2°C soon after 2060 and continue rising afterwards. Such unconstrained climate change has the potential to turn the Earth into a "hothouse", making large-scale irreversible climate impacts more likely. The IPCC report confirms that approximately 4% of the global land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, increasing to 13% at 2°C temperature change. This would also have severe consequences on the productivity of Europe's economy, infrastructure, ability to produce food, public health, biodiversity and political stability. Therefore, overall failing to take climate action will make it impossible to ensure Europe's sustainable development and to deliver on the globally agreed UN Sustainable Development Goals.

For this reason, Europe has declared that want to achieve climate neutrality by 2050, which means net-zero greenhouse gas emission. To this purpose energy plays a central role as it is today responsible for more than 75% of the EU's greenhouse gas emissions. In all options analyzed, the energy system moves towards net-zero greenhouse gas emissions. The future energy system will integrate electricity, gas, heating/cooling and mobility systems and markets, with smart networks placing citizens at the center.

Therefore, the transition towards a net-zero greenhouse gas economy is led by a Strategy, that provides a number of solutions that could be pursued, as: maximise the deployment of renewable energy sources (RES) and the use of electricity to fully decarbonise Europe's energy supply, maximise the benefits from Energy Efficiency including zero emission buildings, embracing clean, safe and connected mobility, a competitive EU industry and the circular economy, developing an adequate smart network infrastructure and inter-connections, reap the full benefits of bio-economy and create essential carbon sinks and tackle remaining CO_2 emissions with carbon capture and storage.

In particular, as concern the first solution, all scenarios assessed imply that by next mid-century this has to change radically with the large-scale electrification of the energy system driven by the deployment of RES, be it at the level of end-users or to produce carbon-free fuels and feedstock for the industry, reducing GHG emissions and as a consequence reducing the use of fossil fuels. This will lead also to a high degree of decentralization, in both the residential and services sectors, which today are responsible for 40% of energy consumption [1].

In this framework, renewable sources contributed 23% of global electricity supply in 2014, and this share is expected to increase from 37% to 58% in 2040 [2]. Within renewable generation, solar and wind power are easily converted into electricity by photovoltaic panels and windmills, while concentrated solar power is under development for its large-scale deployment. At the end of 2016, solar and wind installed capacities (296 and 467 GW, respectively) accounted for almost 40% of all renewable installed power capacity (about 15% of all power sources) [3].

Within the RES technologies, photovoltaic (PV) panels offer the possibility of simple mounting also of small power systems thanks to their modularity, simple management and low maintenance costs. Therefore, this can lead to a high degree of decentralization or "distributed generation", in both the residential and services sectors, which today are responsible for 40% of energy consumption [1].

Distributed generation by PV has several advantages like:

1. Low environmental impact installation.
2. Reduction of increasing large power plants installations.
3. No new soil occupation, they could be installed on the roof.
4. Increased thermal insulation of the buildings' roofs.
5. Reduction of the long-distance transmission losses.

For this reason, many countries introduced incentives for the installation of PV roof by citizens, ensuring them the possibility to self-produce a part or all the consumed electric energy, giving rise also to the energy communities.

Further, the transition towards a largely decentralized power system based on RES will also require a smarter and flexible system, building on consumers' involvement, increased interconnectivity, improved energy storage deployed on a large scale, demand side response and management through digitalization. The expansion and smartness of the electricity system, production and applications will require keeping the adequacy of the single energy market design high on the energy agenda in the coming decades to achieve zero carbon power in a cost-effective way and avoid stranded assets.

As concern the energy storage system, the need is due to the key issue linked to energy production from the renewables power plants that is heavily weather-dependent. In the case of the PV power plant, the renewable energy production reaches the peak during the solar noon, it is lower during the other times of the day and equal to zero during the night. It is also seasonal dependent; indeed, the PV plant produces a higher amount of energy during the summer period while a lower one during the winter one. Further, the energy production from the PV power plant also depends on the location of installation. This entails fluctuations causing instability of power supply and, consequently, of the electric grid. Furthermore, energy security is generally ensured when supply and demand are always balanced. Instead, there is a limited time coincidence of the renewable resources with demands.

Consequently, systems for storing energy are becoming increasingly significant. The battery is one of the most common technologies to store electrical energy (EE) through chemical reactions. This is characterized by an elevated electrical round-trip efficiency and the low costs. While, among the various solutions that are being evaluated, hydrogen is currently considered to be one of the key technologies, allowing future large scale and long-term green storage of renewable power to be combined.

Hydrogen can be produced from various raw materials by a number of different process technologies. At present, it is mainly produced from fossil fuels, that corresponds to about 96% of the world's hydrogen production [4]. Steam methane reforming (SMR) is the most widely used route for producing hydrogen from natural gas. Other thermo-chemical conversion technologies allow hydrogen production through different pathways starting from coal, oil, biomass-derived fuels, biomass and wastes [5]. However, all these approaches are not GHG-free.

Instead, the Power-to-Gas concept, based on water electrolysis utilizing electricity derived from renewable energies (wind, solar, geothermal, hydro) is the most environmentally friendly approach. This attractive method for hydrogen generation, based on a mature technology, currently accounts for only 4% of the hydrogen production but its large expansion is expected in the next few years: a share of 22% is predicted for 2050 [6].

In this way, a double gain is obtained, i.e. the electricity generated by the renewable power plant is stored and at the same time the hydrogen is produced, and then used for multiple purpose. As concern the residential sector, it could be used to generate again electrical energy by fuel cells (FC) or internal combustion engine (ICE). However, this type of system presents a lower electrical round-trip efficiency than the battery. On the other hand, it becomes advantageous if the possibility of recovering the thermal energy produced during the process of production and use of hydrogen is considered. In this way the system is taken into account as polygeneration one, that increases the overall efficiency and make it competitive with respect to the battery.

Therefore, the aim of the thesis is to carry out a comparison between these two storage technologies. To do this, first, a design solution of renewable energy plants and storage systems with a high energy performance applied in the residential sector is proposed in order to promote the diffusion of these technologies. To this purpose, the energy balance of the PV plant and different storage system and the solar water heating system applied within the energy communities has been carried out in this work. In particular, the PV plant and the storage system are designed in order to maximize the self-sufficiency, i.e. the ratio between the energy supplied to the users and the required one, in order to make the energy communities as much as possible independent from the grid. In this way, the GHG emission coming from the residential sector would be drastically reduced. As concern the storage system, the two different analyzed technologies are the battery and the hydrogen ones. These present different characteristics, that give different results in the performance of the overall plant. At the end of this work, the better configuration that allows to achieve the highest parameters is found. These also change by considering the plants installed in different locations, depending on the solar radiation. Therefore, the analysis is also carried out by considering three Italian cities: Milan, Rome and Syracuse.

2. Self-consumption and Renewable Energy Communities

As said in the introduction chapter, currently, the climate changes and their impacts are one of the most important international problems. For this reason, Europe has declared that want to achieve climate neutrality by 2050, which means net-zero greenhouse gas emission. Of these, more than 75% are emitted during the energy production in Europe. Of the produced energy, the building sector covers the 40% of the total energy consumption, of which 26% is consumed by the households.

To this purpose, on 11 December 2018, the European Community has established a common directive with the aim of promoting the energy produced from renewable source, especially in the residential sector. Therefore, one of the adopted solutions to lead the energy transition has been to state that European countries have to guarantee that the consumers can become self-consumers of RES, individually or collectively, i.e. prosumers, when more than one end customers are located in the same edifice or building close each other's. The difference between consumer and prosumer is represented in the Figure 2.1.

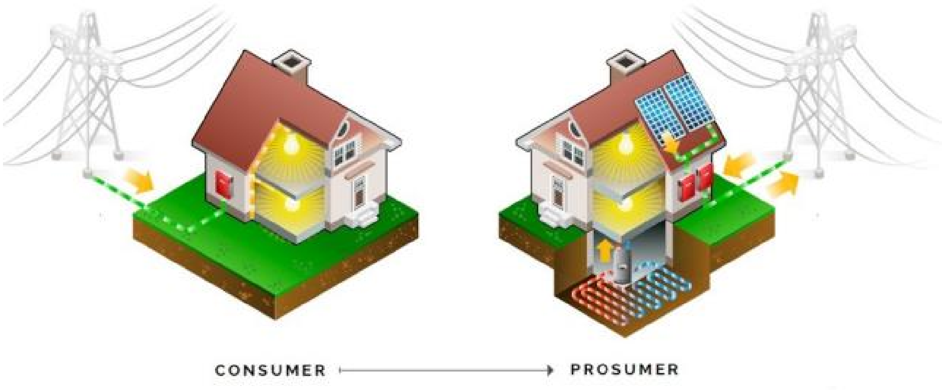

Figure 2.1. Difference between consumer and prosumer [7].

The collective, open and voluntary, participation of people, SMES or local authority, located in the neighborhood of a RES based power plant, centralized or distributed, is defined as community of renewable energy source, the concept is sketched in Figure 2.2. [7, 8].

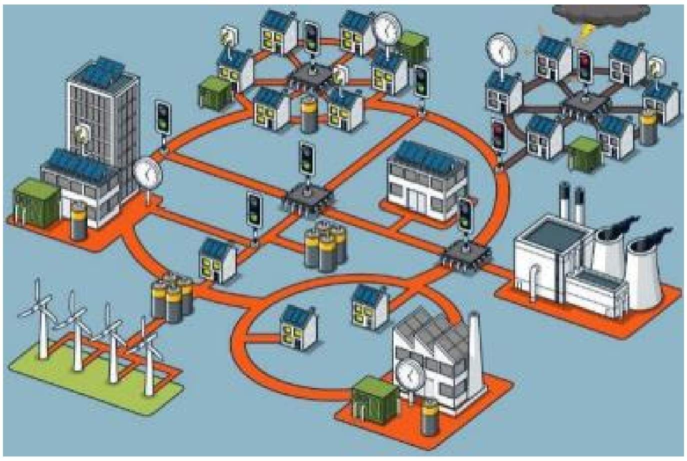

Figure 2.2. Example of renewable energy communities [Source: https://kitfotovoltaicosemplice.it/2020/04/21/la-nascita-delle-comunita-energetiche-in-italia-intervistato-daniele-iudicone-per-saperne-di-piu/].

By this new definition, the self-consumption concept has been enlarged, because it now means both the possibility to consume on side the self-produced renewable energy in order to satisfy the own necessities, but also give the opportunity to a single to become producer for the community, i.e. a regulation for prosumers has been introduced. To do that, in the respective states each EU country has to provide for that the "energy communities" can produce, consume, store, sold, without being subject to discriminatory taxes, and, eventually, to exchange the energy, in the case in which the technologies are shared. Further, the end consumers maintain their rights and obligations. In this way, the users, who were passive consumers in the past, now are incentivized to take part of the production system, becoming owners of renewable energy [7, 8].

Another important aspect is that the consumption in loco of the produced energy can also generate positive effects on the electric system like the reduction of losses in the grid and its potential reduction in development and operating costs [9, 10], i.e. it is beneficial in energy efficient consumption.

On the other hand, one of the main problems connected to the self-consumption is the matching between the load profile and the production one, that is made difficult by the variable and uncertain nature of the renewable energy. Indeed, if it is considered the solar source, for example, it generates the energy during the day, while it is estimated that the load consumption profile for home shows the peaks during the early hours of the day and during the evening. One of the most common strategies to solve this trouble is to apply storage devices, like batteries [9, 10]. Concerning the Italian state, it has not yet issued a national law on the renewable energy Directive but only an experimental phase, that is discussed in the following paragraph.

2.1. The Italian regulation: article 42 bis of "Decreto Milleproroghe"

The Italian regulation consists of the article 42-bis of Decreto Milleproroghe that allows the collective self-consumption from the RES, i.e. to realize renewable energy communities. This happens, with respect to the European directive, under some imposed conditions [8, 11]:

- In the case of self-consumers of renewable energy that collectively act, subjects other than families are associated only in the case in which energy market do not constitute the commercial activity or main profession. Instead, in the case of energy communities, the members are physical people, SMES or local authority, which are only associated if the related activities do not constitute the main commercial or professional activity. Therefore, the main goals are to provide environmental, economic and social benefit, rather the financial profits.
- The prosumers produce energy to self-consume from renewable plants, that have not to exceed 200kW of installed power. They share the produced energy by using the existing distribution grid, and this is equal to the minimum, in each hourly period, between electricity produced and fed into the grid by renewable source plants and the electricity withdrawn from all associated final customers. The energy is shared for instant self-consumption, that can also take place through storage systems. Moreover, in the case of renewable energy communities the consumers withdrawal points and the energy input points of the plants have to be located in the low voltage power grid, under the same medium voltage/low voltage transformer station. Further, in the case of self-consumers of renewable energy acting collectively, they have to be located in the same building or condominium.
- The end users retain their rights, including that of choose their own seller, moreover, they can withdraw from the self-consumption configuration at any time. Further, they regulate relations through a private law contract that uniquely identifies a delegated subject, responsible for the distribution of shared energy. Finally, the participating end customers can delegate the management of the consignments of payment and earning money to the sellers and the Service Manager Energy (GSE) Spa.
- The regulation authority for energy, networks and the environment (ARERA) take the necessary measures to ensure the immediate application of the provisions of this article. Furthermore, the same authority adopts the necessary measures in order that the distribution system manager and the Terna Spa company cooperate to allow the application of the provisions of this article, with paying regard to the modalities to the shared energy measures. Indeed, it creates the possibility of having a virtual sub-grid for managing the energy community. This means that the users are not de-connected form

the grid, but by an appropriate management of bidirectional electric counter the community is able to share the self-produced energy.

Therefore, in this way, the Italian state has ruled the regulation for the collective self-consumption of the renewable electrical energy, i.e. the renewable energy communities. Instead, as concern the sharing of thermal energy, it was already allowed without a specific regulation since a long time.

Once the overall scenario as concern the renewable energy communities in Italy has explained, it is possible to define the aim of the thesis. Indeed, the idea is to exploit this new regulation to promote the energy transition by increasing the self-consumption of renewable energy from the citizens. In this way, both the decentralization of the energy production and the diffusion of the RES is largely favored. Moreover, the use of different energy storage systems is considered with the aim to maximize the self-sufficiency of the energy community, increasing its independence from the external grid as much as possible. Obviously, these will give different performance parameters of the system because of different functioning characteristics. Therefore, the final purpose is to find the best configuration that allow to decrease the global pollution, i.e. the GHGs emission, from the residential sector.

3. Renewable energy source and the main applied devices

The aim of the chapter is to describe the renewable energy plants, applied in the residential sector, considering different approaches for store the electrical energy. Further, a brief description of the main components, that have been applied, and their working principle are reported. Also the advantages or disadvantages of the different ways to store electrical energy through the different technology, or through the different typology concerning the same technology, are reported.

The renewable energy exploited for the considered energy plants is the solar one, therefore the PV system, to generate EE, and the Solar Water Heating system (SWH), to generate thermal energy (TE) to produce Domestic Hot Water (DHW), are the devices considered for the analysis,

Further, as said in the previous chapter, one of the main problems of the renewable energy is the matching between the power production and its request by the users. Indeed, considering the modern families, the biggest amount of daily consumed electricity is required in hours with low or nothing solar light, i.e. when there is few or not production of energy by the PV plant, and so the EE needed to satisfy the demand should be imported from the grid. While the smallest one is required during the day, when there is the highest production of energy from the renewable source, and so the exceed amount of its should be exported [9,10]. A simplified scheme of this trend is shown in the Figure 3.1.

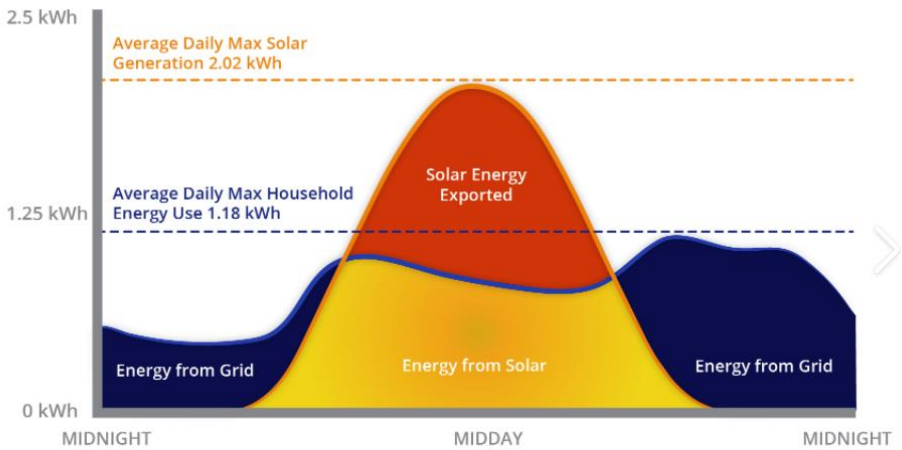

Figure 3.1. Simplified comparison of the produced EE by the PV and home consumed one [Source: https://www.unison.co.nz/tell-me-about/electricity/solar-energy/solar-technology/choosing-your-system-size].

This simplification is necessary because the trend changes according to the local habits, the season, the day (working or holiday) and the family composition.

For the hot water production and consumption, a similar asynchrony exists. The request of hot water is mainly in early morning and in the evening, while maximum production is close to midday. For this reason, the SCs are matched with thermal energy (TE) storage to store the heat coming from the solar radiation, through a heat transfer fluid that pass across the solar collectors, in traditional ones, or by metallic fingers for under-vacuum tubes configuration, allowing to use this TE also during the night. A schematic representation of the solar thermal system is represented in the Figure 3.2., where the thermal flows are represented. The boiler system is used for avoiding lack of hot water and it can be electric or gas based (methane or LPG), more rarely it burns biomass.

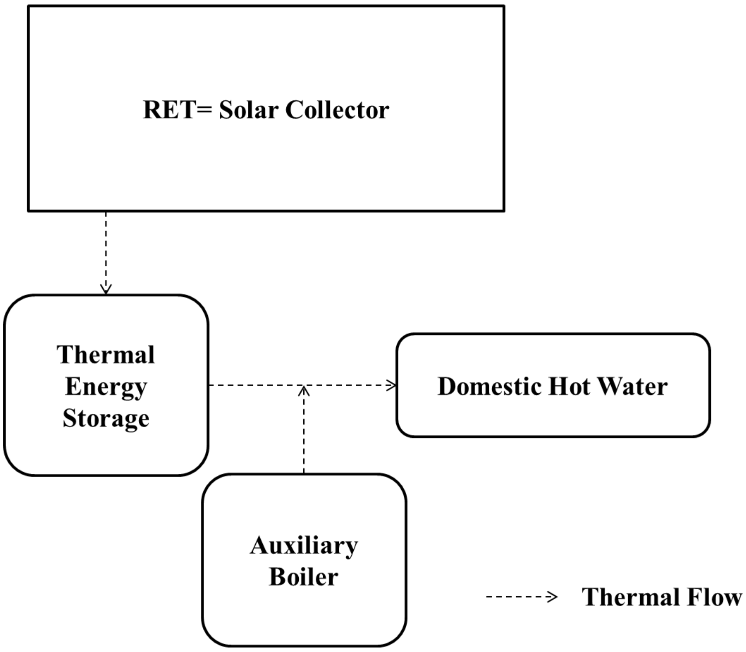

Figure 3.2. Scheme of a solar thermal system.

Therefore, the aim of the thesis is to analyse the capability of different technologies to store energy, in particular the electrical one. The idea is to study the possibility to store excess of electricity generated during the day from the PV system. This is made to increase the amount of energy that is self-consumed by the prosumers, by releasing it during the night, decreasing or deleting the amount of energy that has to be imported from the grid and, if possible, also reducing the fuel consumption of the boiler. The different pathways that have been considered to store the electrical energy are through:

- Battery, as shown in Figure 3.3., where the electric flows are represented. In this device the EE is stored as chemical one and converted again in electric form when is required. It represents the common technology in term of electrical energy storage and is characterized by a high electrical round-trip efficiency.

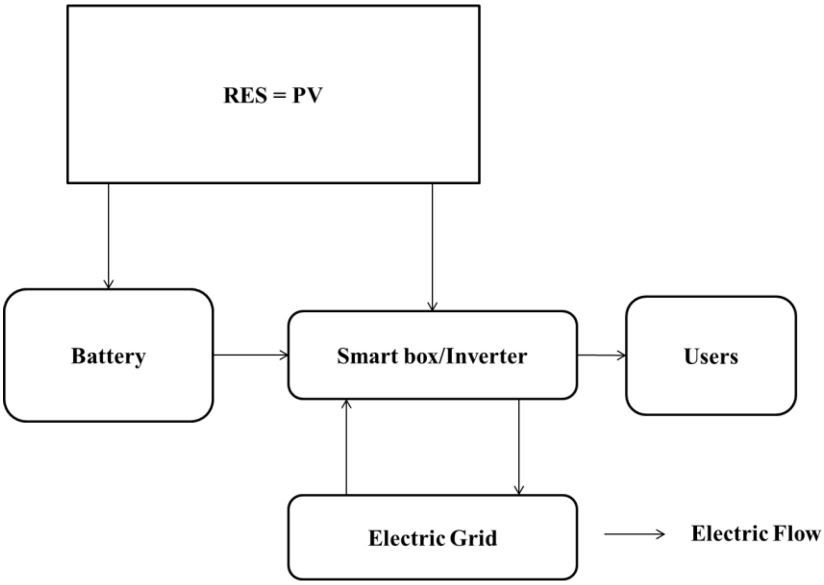

Figure 3.3. Photovoltaic plant with battery storage.

- Hydrogen, as energy vector. In this case, the excess of EE generated by the PV is used by an electrolyser (EC), splitting water into hydrogen and oxygen. Also in this case there is a chemical storage, but in the form of hydrogen that is a burnable gas and then a fuel. Indeed, hydrogen can be consequently used by a fuel cell (FC) or internal combustion engine (ICE) electrogenerators, which are devices using this fuel through electrochemical or combustion reactions respectively, to produce electricity. Further, in this specific application, the metal hydride tank is considered. This is a device that absorbs and desorbs hydrogen through chemical interaction with metal compounds. The Figure 3.4. show respectively the scheme of the plant with FC or ICE, where the electric and hydrogen flows are represented.

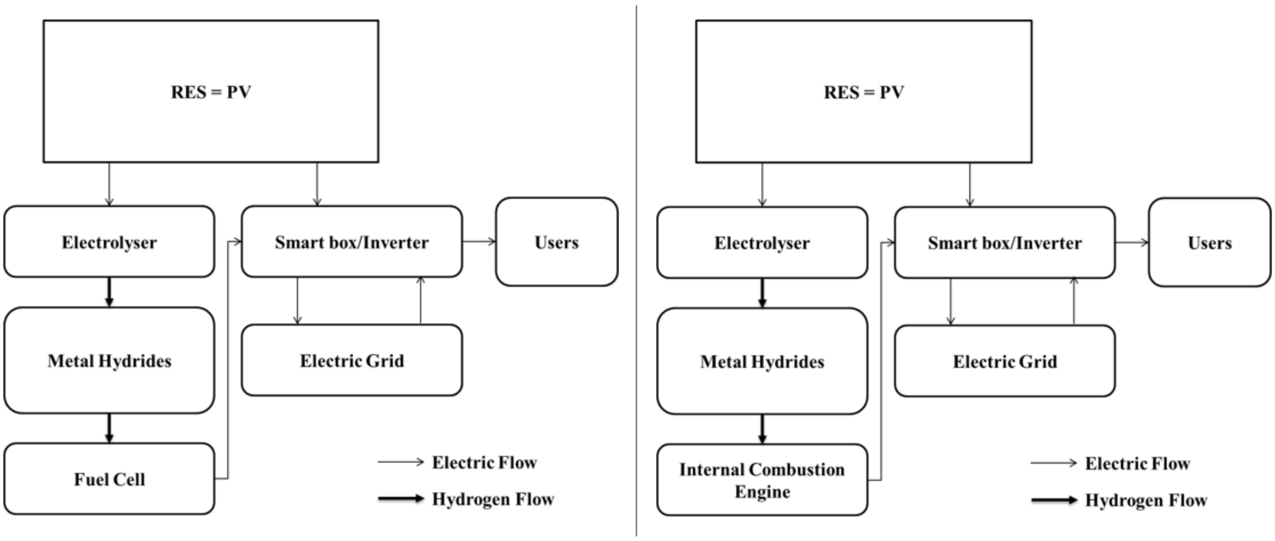

Figure 3.4. Photovoltaic plant with hydrogen-based storage system: left) FC and right) ICE

In the following chapters the way in which this component interact will be explained in detail, also providing the sizing of them and an analysis from an energy and performance point of view.

To this purpose, here a brief description of the main installed devices is reported, explaining the operation mode and their applicability, with advantages and disadvantages of the different pathways to store energy.

3.1. Solar energy

The total power received by a unit area from a radiation source is called irradiance (G). The Sun approximately acts as an ideal radiation emitter (black body) at a temperature around equal to 5800 K. Outside the atmosphere, the electromagnetic radiation has a spectral distribution from ultraviolet to infrared, with a peak in the visible field. When the solar radiation goes inside the terrestrial atmosphere, some of the incident energy is lost by dispersion and reflection or absorbed by clouds, carbon dioxide, ozone, other air molecules, etc. The extra-terrestrial solar spectrum and the terrestrial one are represented in the Figure 3.5.

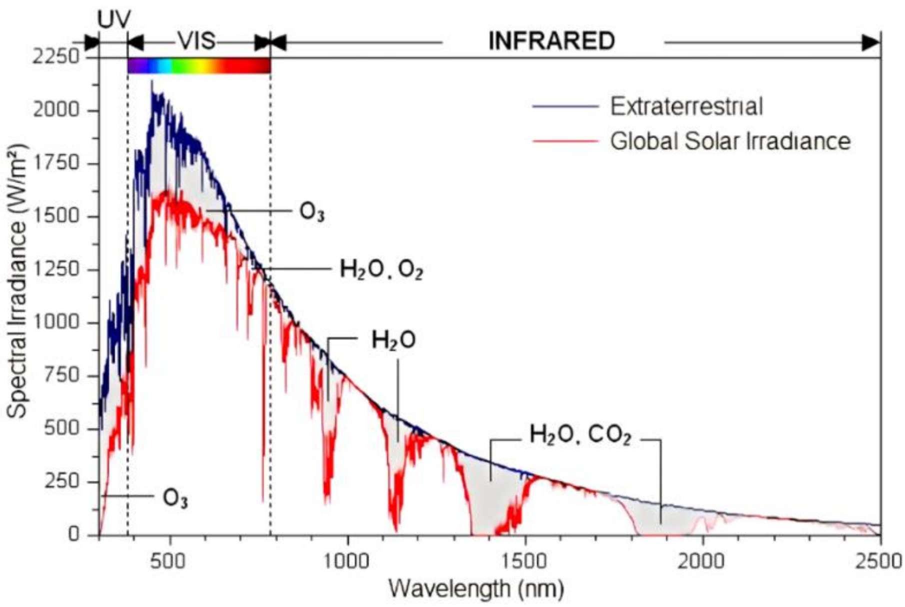

Figure 3.5. Solar Spectrum [Source: https://www.researchgate.net/figure/Standard-solar-spectrum_fig2_280041456].

The integral of the solar spectrum with respect to the wavelength on a unit area perpendicular to the incident beam is the so-called solar irradiance.

The solar radiation that is not diffused or reflected but reaches the earth surface is called direct irradiance (G_b). Instead, the diffused solar radiation that reaches earth surface is called diffused radiation (G_d). A small part of the irradiance is called albedo (G_a). This is the amount of radiation that can reaches the receiver on a tilted plane, after the reflection from the earth surface. The total irradiance, that reaches a terrestrial receiver, is the sum of these three components and is the so-called global irradiance (G_g).

The intensity of the solar radiation that reaches the Earth varies according to the regular daily and annual variation due to the sun motion, and the irregular weather variation and, therefore, it is characteristic of the geographical location [9], as represented in the Figure 3.6. for Italy.

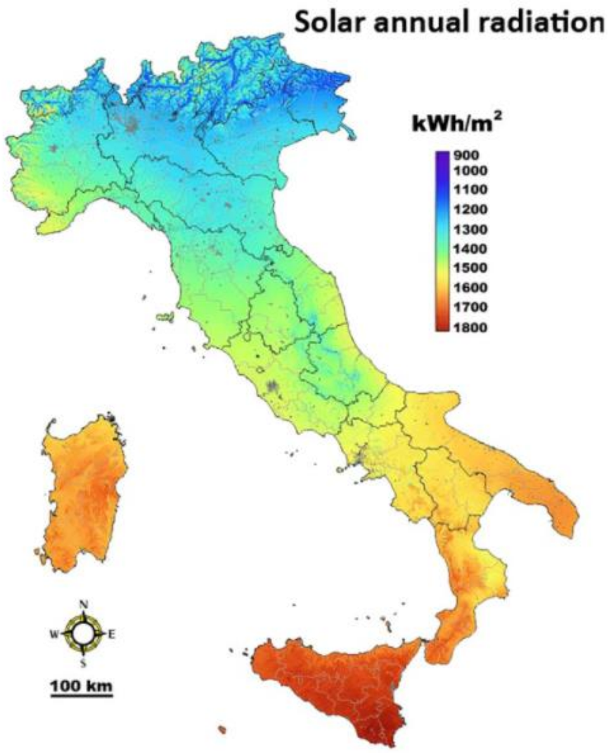

Figure 3.6. Italian annual solar radiation [Source: https://www.eniscuola.net/mediateca/radiazione-solare-annua-in-italia/].

For this reason, in the thesis the energy balance is carried out considering three different Italian cities: Syracuse, Rome and Milan. The first one is located in Sicily, in the southern part of Italy, where there is the highest solar annual radiation, the second one is located in Latium, in the middle part, the last one is located in Lombardy, in the northern part, where there is the lowest solar radiation. Therefore, since the PV plant and the SWH system are used to convert the solar energy into respectively the electrical one and the thermal one, they show different performance considering the different locations. Then, their basic working functioning and the conversion efficiency are reported in the following paragraphs.

3.1.1. Photovoltaic cell and module

The photovoltaic panel allows the direct conversion of solar energy into electricity. This is obtained by exploiting the physical phenomena of the interaction between photons, of solar radiation, and the electrons in the valence band of each cell, composed by a semiconductor material [12, 13, 14].

3.1.1.1. Basic functioning and efficiency of a single photovoltaic cell

The conversion efficiency depends on the applied technology. One of the most common one is the crystalline silicon. Essentially, the PV cell is a diode, which is placed between two electrodes.

Thus, the PV cell operating in dark conditions can be explained through the "P-N" junction theory. Then, referring to the crystalline silicon, a diode is composed by a doped layer with impurities of "type N" (high concentration of phosphorus) placed over a doped substrate with impurities of "type P" (high concentration of Boron), as represented in Figure 3.7. The thickness of "type N" layer is small enough to allow solar radiation to penetrate the junction area, where the electric field is generated.

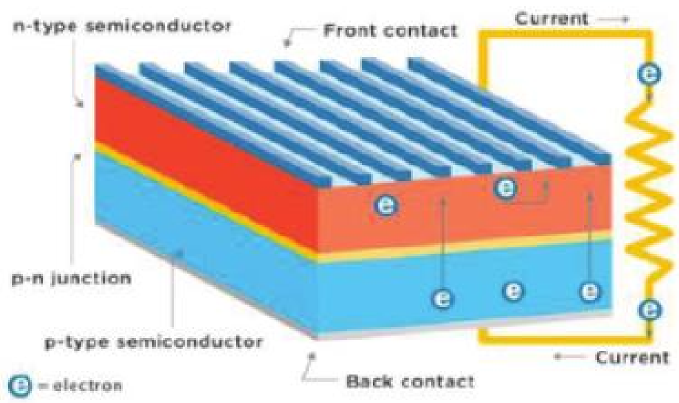

Figure 3.7. Schematic representation of photovoltaic cell [Source: https://www.researchgate.net/publication/320284529_Simulating_the_electrical_characteristics_of_a_photovoltaic_cell_based_on_a_single-diode_equivalent_circuit_model].

To understand how this is generated, it is needed to understand what happens inside the PV cell. Indeed, in the PV cell occurs the diffusion of the electrons in region of "type N" towards the interface of the "type P", generating a positive charges distribution in the "type N" layer. In the same way, the holes diffuse from the "type P" substrate towards the interface of the "type N" layer, generating a negative charges distribution. Thus, the junction region is composed by both positive charges in the "type N" side and negative charges in the "type P" one. This phenomenon ends when the electrical field generated by this new charge distribution is able to balance the natural diffusion current.

However, the balance is significantly changed when a voltage is applied outside the junction. Thus, a positive voltage applied to the P side reduces the potential barrier, generating a significant current flow through the diode: the diffusion current [12, 13, 14].

Thus, generating an external electrical field in the junction area, the electrons are attracted by the side N, positively charged, and the holes by the side P, negatively charged, as obtained in the previous configuration. This charges motion is the source of the photovoltaic current. In the case of the PV cells, this external electrical field is generated through the solar radiation.

Now, considering that the energy of a photon (E_{ph}) is proportional to both the Plank's constant (h) and its frequency (v), the photovoltaic phenomenon is activated only by the photons with an energy higher than the energy gap (E_{gap}) between the valence band and the conduction one of the materials, as expressed in the following equation [9, 12, 13, 14].

$$E_{ph} = h * v = h * \frac{c}{\lambda} \geq E_{gap} \quad (1)$$

Thus, if this inequation is satisfied by photons, those are able to generate couples of electron/holes. This couples generate an electrical field that is needed to produce the PV current. This current is then needed to allow the potential barrier reduction, consequently increasing the diffusion current [12, 13, 14].

Instead, as concern the performance of the PV cell, the conversion efficiency of the photovoltaic cell, defined as the ratio between the maximum power per unit of area, provided by the cell, and the solar irradiance per unit of area, is the most important parameter. However, this presents very low values, with a maximum equal to around 15% of the energy conversion [13, 14]. Further the required energy to activate the PV phenomenon, there are different losses that cause this low efficiency [9, 13, 14]:

- Reflection losses, due to the phenomenon of the reflection of photons with the incident surface.
- Recombination, not all the generated pair electron-gap are harvested by the electric field and sent to external load, because along the way, from the generating point through the junction one, they could meet charge of the opposite sign and recombine.
- Parasite resistance, the charges have to be harvested by the metal contacts, placed on the front and back of the silicon cell, generating a certain interface resistance that causes a dissipation, reducing the power transferred to the external load.
- Losses due to the surface resistance of the cell.

Once the photovoltaic cell has been defined, it is also possible to define the PV module as an environmentally protected set of interconnected cells.

They are mainly classified in two types, considering the different way in which are produced: crystalline silicon and thin-film cells. The first one, is the is further classified into: monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si) while the second one is the amorphous silicon (a-Si) module [9].

Then, the different types of PV plant configuration are described in the following paragraph.

3.1.1.1. Photovoltaic systems

Mainly, two different type of PV system exists [13, 15]:

- Grid-connected system: in which the photovoltaic system is connected to the public grid. This requires an inverter for the transformation of the PV generated DC electricity to the grid AC electricity, at the level of grid voltage. Here, the grid serves as an ideal storage and ensures system reliability. Indeed, when the power production is higher than the users required load from, the energy excess is exported to the grid while, in the opposite case, the energy defect is imported from the grid. However, in the considered cases, a local energy storages could be obtained by applying batteries, as represented in the Figure 3.8., or the hydrogen-based storage system, as proposed in this thesis.

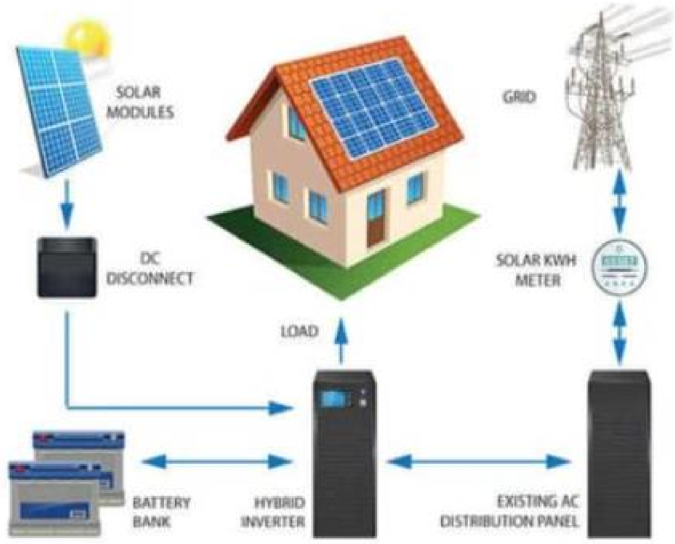

Figure 3.8. Grid-connected PV power system [Source: https://www.apollopowersystems.com/solar-solutions/solar-rooftop-solutions/].

- Stand-alone system: in which the photovoltaic system is totally independent from the electric grid. This type of configuration requires an inverter, for the transformation of the PV-generated DC electricity to the grid AC electricity, an energy controller and an energy storage. This last component is needed to store the energy excess during time with no or low load while, in the opposite case, the energy defect is obtained by discharging the energy storage. The autonomy of the system can also be improved by incorporating an engine generator (backup generator) into the PV system design. The overall scheme of the plant is shown in the Figure 3.9.

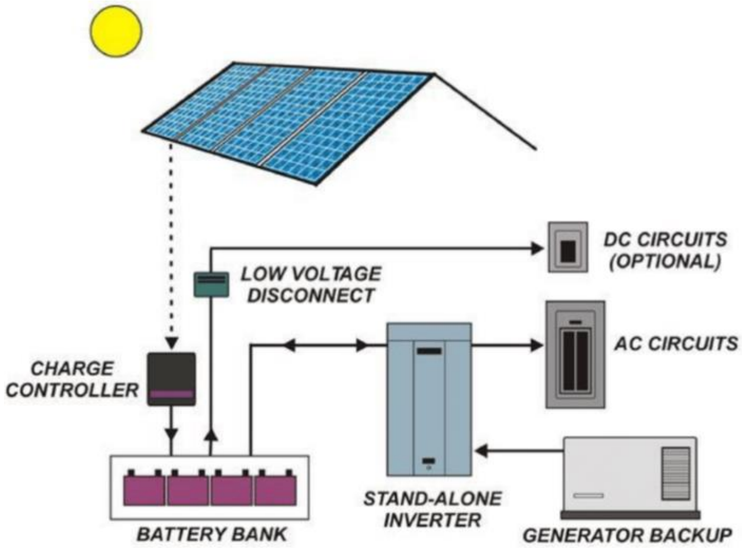

Figure 3.9. Stand-alone PV power system [Source: https://www.researchgate.net/figure/Off-grid-PV-System-Schematic_fig2_322738988].

3.1.2. Solar collectors and Solar Water Heating system

SWH system is largely diffused, especially in Mediterranean area, and represented the first attempt for diffusing renewable energies and reduce the use of fossil fuels for water heating.
The main devices of solar water heating are solar collectors, water storage tank and auxiliary heating device. The first ones are the most important in this kind of system and they are used to transform solar radiation into heat and then to transfer it to the water that flows through them. They are mainly classified into flat plate, evacuated tube, both used designed to provide low temperature thermal energy, up 100°C above the ambient temperature, and concentrating collectors, used for high temperature solar thermal applications. In general, they can be connected in series or in parallel strings in order to increase the harvested thermal energy and, therefore, the required demand from the users. The water tank is important to store the thermal energy coming from the sun and use its when there is a demand of hot water by the users. The auxiliary heater is used to provide the necessary thermal energy when there is not the possibility to catch it from the sun, for instance during cloudy days, or during the night and to bring the water, inside the storage tank, at the required temperature [16, 17].

A brief description of these components, how they work, and the main characteristics of SWH system is reported in the following paragraphs.

3.1.2.1. Basic functioning and efficiency of collectors

In steady state conditions, the performance of a solar collector is described by an energy balance that indicates how Incident Solar Power ($\dot{Q}_S$) transformed into Useful Power ($\dot{Q}_U$), considering the heat losses due to conduction, convection and infrared radiation ($\dot{Q}_L$) and the optical reflection one ($\dot{Q}_O$), described by the equation (17) and shown in the Figure 3.10. [16, 17].

$$\dot{Q}_U = \dot{Q}_s - \dot{Q}_L - \dot{Q}_0 \quad (2)$$

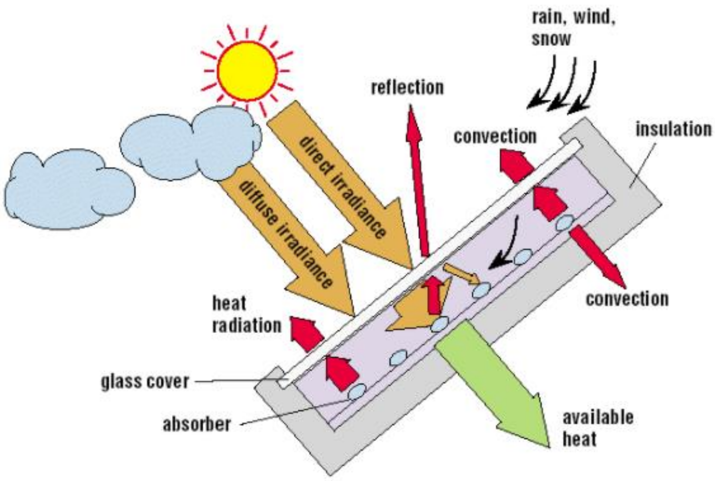

Figure 3.10. Flat plate energy balance [Source: https://www.volker-quaschning.de/articles/fundamentals4/index_e.php].

The flat plate solar collectors are manly constituted by the solar absorbing plate, back insulation, covers, and the tubes for fluid flow. Therefore, there are some considerations that can be done to improve the efficiency considering the previous equation. First, the cover is useful to reduce heat losses by convection and infrared radiation. Double covering may further reduce heat losses but, at the same time, reduce radiation reaching the absorber due to double reflection. It depends on the difference between the mean absorber plate temperature and the ambient one, indeed if this is low, and so the convection losses are small, the use of single cover gives a higher efficiency while at higher temperature difference the use of double cover can gives a better performance. Further, it is important to select an absorber plate with a proper coating to have a high absorptivity, in the solar part of the spectrum between 0,33–3,3 µm, and low emissivity, in the infrared one, to further reduce the convection losses and the infrared radiation respectively. At the end, metal with high thermal conductivity (such as copper and aluminium) as absorbing surface and tubes of fluid flow should be employed to decrease the conduction losses.

To calculate the efficiency is possible to consider the basis for the standard EU collector efficiency formulation [17].

A further reduction in the convective losses may be obtained by removing the air between the cover and the absorbing surface, leading to the so-called evacuated tubular collectors. On the other hand, due to the necessity of using cylindrical shape, it is more difficult to arrange the position to allow that the entire surface always receives the full solar flux, so they have a higher optical loss with respect the flat plate collectors. Therefore, their application is preferable only for temperature above 80 °C, where the convective losses prevail the optical one [16, 17].

3.2. Electrochemical cell

The Electrochemical cell is a device that directly exploits the chemical energy contents in the reactants species to produce electrical power, or vice versa. In general, it is composed by two electrodes, the anode, where reaction of oxidation occurs and delivery of free electrons happens, and the cathode, where the reaction of reduction occurs consuming electron, and the electrolyte, material capable to conducts ions and, at the same time, capable to stop the conduction of electrons, which have to move through the external circuit. Electrochemical cell can be divided into closed one (or battery), when the material, that composes the electrodes, participates to the reactions, therefore there is not mass exchange with the external environment, and open one (like fuel cell and electrolyser), when the material, that composes the electrodes, does not participate to the reaction, therefore the reactants molecules are continuously supplied to the system from the external environment

3.2.1. Battery

One of the most widespread ways to store electricity is through reversible electrochemical reactions given by the batteries [12]. They are closed (no mass exchange with the external environment) electrochemical cell that can work in direct or inverse operation. For our purposes, the main parameters to consider, concerning this technology, are [12, 13]:

- Nominal voltage (V_{nom}), that represent the voltage of battery during the charging power.
- Capacity or size, amount of energy that can be stored by the battery, measured in ampere-hours (Ah) or, if multiplied for the nominal voltage, in watt-hours (Wh).
- Depth-of-Discahrge (DOD), amount of charge (in percentage) that can be removed, starting by the maximum state of charge (SOC_{max}) until to arrive at the minimum state of charge (SOC_{min}), from the battery without generating a damage to the storage. These two are important parameters that are calculated by applying the following equations:

$$SOC_{max} = \left(1 - \frac{1 - DOD}{2}\right) * 100 \tag{3}$$

$$SOC_{min} = \left(1 - \frac{1 + DOD}{2}\right) * 100 \tag{4}$$

- Lifetime, number of cycles, charge and discharge, that a battery can carry out before its capacity is reduced by 70-80%. It depends on the specific DOD.
- Energy density, specific storable energy per unit of volume (Wh/m^3) or mass (Wh/kg).
- Round-trip efficiency, defined as the ratio between the values of current, voltage or energy of a consecutive charge and discharging, with a value in the range of 80-90%.

The most common battery today used for energy purpose is the lithium-ion one, presenting advantages and drawback.

3.2.1.1. Lithium-ion battery

The lithium-ion battery is composed by two electrodes, a reductant (anode) and an oxidant (cathode) separated by an electrolyte, made of an organic polymer sheet, that allows the moving of lithium ions from one side to the other while forces the flowing of the electrons through the external circuit. Both electrodes and electrolyte are immersed in an electrolytic solution containing free lithium charges (Li^+). Therefore, the complete reaction during the discharging phase is equal to:

$$LiC_6 + CoO_2 \rightleftarrows C_6 + LiCoO_2 \quad (5)$$

Therefore, lithium ions move from the anode to the cathode through the electrolyte, while, at the same time, the electrons, move from the negative side to the positive one, through the external circuit. In this case a voltage equal 3,8 V is generated for each cell of the battery [12, 18]. By reversing the reactions is possible to obtain the charge phase, as represented in the Figure 3.11.

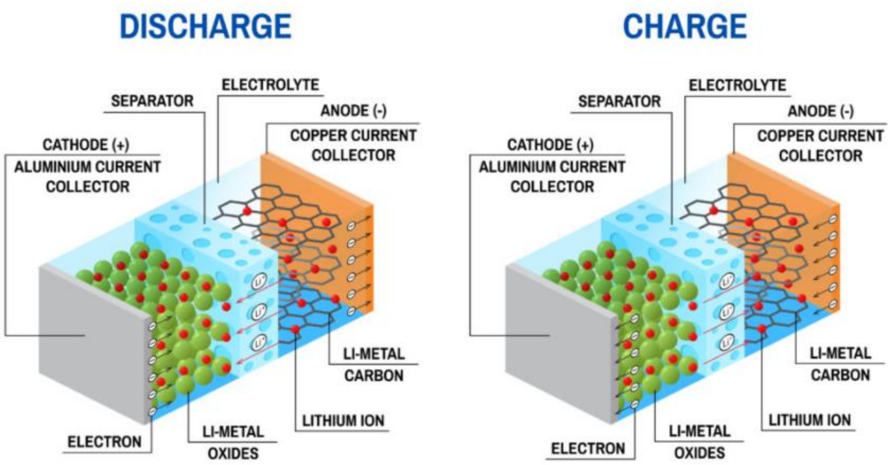

Figure 3.11. Representation of discharge and charge phase of a lithium-ion battery [Source: https://blog.normagroup.com/batterie-im-elektrofahrzeug/].

Though, this represents the ideal case, where the voltage given by the differential potential between the two electrodes is considered constant during the time. In the real case, it is needed to consider some phenomenon that generates losses in battery as: the activation polarization, the ohmic polarization, the concentration polarization and the thermodynamic phenomena.

Therefore, the real functioning of the battery in terms of voltage is represented as a function of SOC, called battery discharge. Further, the efficiency is equally affected by these losses. For this reason, the round trip efficiency is around 80-90%.

Further, it presents phenomenon of degradation during the time. This happens in the case of prolonged discharge phase after the SOC_{min}. This phenomenon happens also in the partial discharging condition or in the case of long inactivity period, leading to a self-discharge of the battery [13].

However, it presents some advantages as a high energy density (100-265 Wh/kg), high round-trip efficiency and the average lifetime equal to around 1000 cycles [13].

3.2.2. Fuel cell

Fuel cell is an open electrochemical cell working in Galvanic regime, where the disequilibrium of the reactants in terms of Gibbs free energy is directly converted into electrical power. If hydrogen is considered as fuel, it possible to analyse the reactions that occur in a generic fuel cell. As said in the previous paragraph, an electrochemical cell is composed by two electrodes, the anode, where the reaction of oxidation occurs realising both e^- and H^+ that moves respectively through the external circuit and the electrolyte respectively, and the cathode, where the reaction of reduction occurs. Thus, the complete reaction is equal to:

$$H_2 + 0{,}5 * O_2 \rightleftarrows H_2O \qquad (6)$$

As represented in the Figure 3.12.

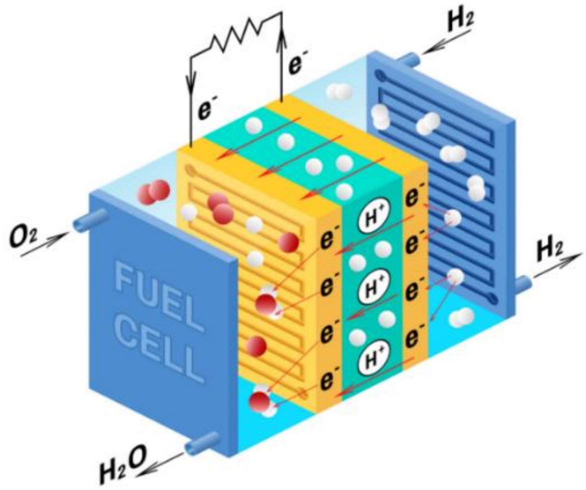

Figure 3.12. Representation of a hydrogen fuel cell using acid electrolyte [Source: https://leehamnews.com/2021/01/29/bjorns-corner-the-challenges-of-hydrogen-part-22-hydrogen-fuel-cells/].

Under the hypothesis of cell represented as a black box, operating in condition of equilibrium when the external circuit is still open and in steady-state condition, the Nernst equation, that express the Open Circuit Voltage (OCV), in the case of hydrogen reaction with oxygen supply a value of 1,23 V, at standard condition.

Once the circuit is closed, a current start to flow through the external circuit, breaking the chemical equilibrium existing between the two electrodes, generating losses due to mass and charge transport phenomena, which characterize the real functioning of a fuel cell. The polarization curve, represented in the Figure 3.13., takes into account the variation of the voltage as a function of the current due to: the charge transfer, called activation losses, the charge conduction, called Ohmic losses, and the mass transport limitations, both of reactants and ions.

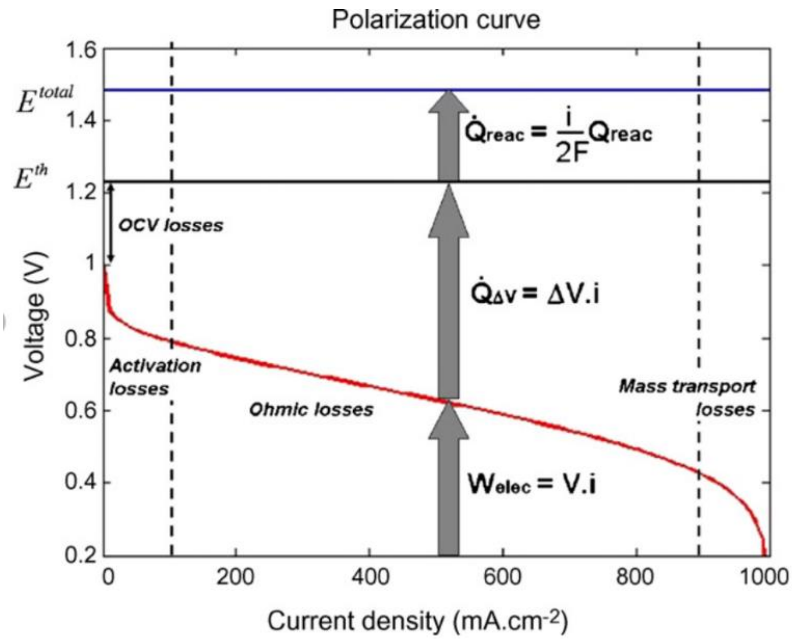

Figure 3.13. Example of polarization curve of a fuel cell [Source: https://www.researchgate.net/publication/223576151_Heat_sources_in_proton_exchange_membrane_PEM_fuel_cells].

Though, on one hand, these losses reduce the electrical efficiency of the electrochemical cell, on the other one, these can be recovered as thermal fluxes. Obviously, also the heat due to the irreversibility and so the entropy generation, that are generated during the reaction occurrence, can be recovered. Therefore, the galvanic cell is always characterized by an exothermic behaviour [19].

The fuel cells are classified depending on the material that composes the electrolyte, which in turn determine the temperature range operation [19].

Low temperature fuel cell, between 50-90 °C:

- Proton Exchange Membrane Fuel Cell (PEMFC).
- Alkalyne Fuel Cell (AFC).
- Direct Methanol fuel cell (DMFC).

At around 250 °C:

- Phosphoric Acid fuel cell (PAFC).

High temperature fuel cell, between 600-1000 °C:

- Molten Carbonate Fuel cells (MCFC)
- Solid-Oxide fuel cell (SOFC).

For residential application the most suitable are the low temperature FC, and in particular the PEMFC, represented in the Figure 3.14. This is due to the low operation temperature, that allow fast start up and shut down, and simplified maintenance. PEMFC presents an electrical round-trip efficiency around 50%. It means that the remaining part of energy, that is not converted into electricity, is transformed into heat [19].

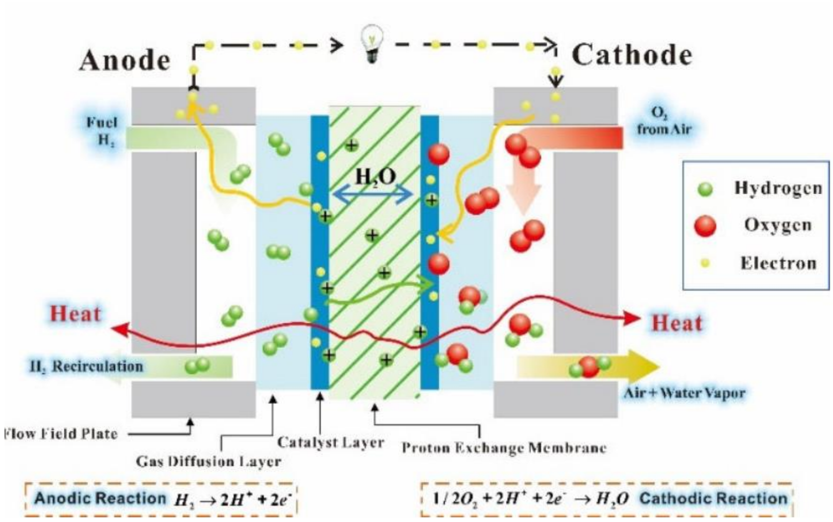

Figure 3.14. Proton exchange membrane fuel cell [Source: https://www.researchgate.net/figure/Schematic-of-a-proton-exchange-membrane-fuel-cell_fig1_331488888].

3.2.3. Electrolyzer

The electrolyser is an electrochemical cell where electrical energy is used to drive not spontaneous reactions to obtain a fuel, containing chemical energy. Therefore, the working principle is reversed with respect the fuel cell, indeed, in the anode, the oxygen oxidation occurs, while at the cathode the H^+ ions reduction happens. The complete reaction is equal to:

$$H_2O \rightleftarrows 0{,}5 * O_2 + H_2 \tag{7}$$

The overall reaction requires a thermodynamic cell voltage of 1.23 V to get hydrogen and oxygen from water at 25 °C. In practice, the cell voltage required for efficient hydrogen generation must be higher than 1,23 V, due to the additional voltage necessary to overcome over-voltages, associated with electrode kinetic, and the ohmic resistance of the electrolyte and electrolysers components.

The electrolyser cell presents an endothermic behaviour until the thermo-neutral density current, after that it presents an exothermic one. Therefore, though the electric efficiency lowers by increasing the current density, to work after this thermo-neutral condition is better in order to recover the thermal flow [19].

The electrolysers are classified in the same way of the fuel cell and the most common one is the PEMEC for the residential application, thought a new technology, the Anion Exchange Membrane electrolyser cell (AEMEC), has been recently developed.

3.2.3.1. Anion Exchange Membrane electrolyser cell (AEMEC)

The Membrane Electrode Assembly (MEA) consists of an anode, for example iridium, and cathode, composed by NiMo, catalyst, separated by a thin, dense, non-porous polymer membrane electrolyte, as in PEMEC, immersed in a potassium o sodium hydroxide (KOH and NaOH respectively) solution. The charges are transferred over the membrane by hydroxide ions, as AEC. For these reasons AEM water electrolysis is a combination of AEC and PEMEC.

Therefore, in AEMEC, hydrogen gas and hydroxide ions (OH^-) are produced from water reduction at the cathode, as follow:

$$2H_2O + 2e^- \rightleftarrows H_2 + 2OH^- \tag{8}$$

OH^- ions move to the anode through the AEM electrolyte, where oxidation reaction occurs:

$$2OH^- \rightleftarrows 0{,}5 * O_2 + 2e^- + 2H_2O \tag{9}$$

The two-half reaction are shown in the Figure 3.15.

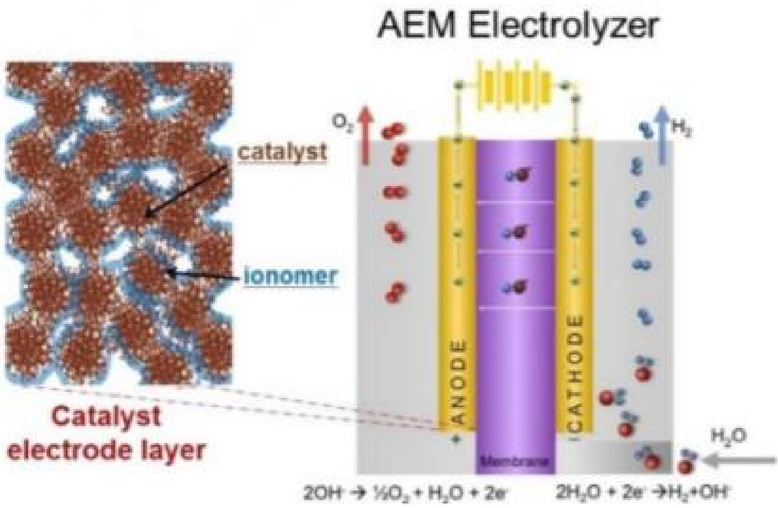

Figure 3.15. Anion exchange membrane electrolyte cell [Source: https://www.mdpi.com/2073-4344/8/12/614/htm].

The AEMEC present an electrical efficiency of around 60%, while during the functioning a certain amount of thermal energy can be recovered.

The resulting high pH of the system reduces corrosion issues of the components in respect to the PEMEC: titanium in the porous transport layers (PTL) and bipolar plates (BPP) can be substituted by steel, and the scarce platinum group metals (PGM) in the electrodes can be substituted by cheap and abundant materials like nickel. Therefore, it has the potential to become a cheaper alternative to PEM water electrolysis system with the same advantages, though presents a lower performance, as: low footprint, large operational capacity and fast response to changing operating condition [20, 21].

There are several challenges before to make this technology fully competitive [20]:

- The low alkaline stability of most AEMs needs to be overcome.
- The ionic resistance of AEMs need to be decreased, while retaining a low permeability for hydrogen.
- The alkalinity of feed solutions should be decreased, ultimately to pure water.
- Suitable ionomer binders need to be developed.
- Many researchers still use PGM catalysts in their work because they are a convenient benchmark.

3.3. Metal Hydrides (MH) hydrogen storage

One of the most powerful technology barriers to the widespread acceptance of hydrogen as energy vector is the storage problem. Conventional ways to store hydrogen such as gas compression and liquefaction are bulky, expensive and raise important safety issues. For these reasons, alternative ways to store hydrogen has been proposed and studied. Between these, metal hydride storage, represents a fairly good solution for the mentioned problem and it is a well-developed technology that reached the market. Indeed, it is able to store and release a high amount of hydrogen in a small volume at low pressure and at near room temperature. For these reasons this technology has been chosen for this study.

Metal hydrides for hydrogen storage is usually ternary system, described by the chemical formula AB_xH_n, where A belongs to the rare earth or alkali metal classes, and element B is a transition metal which, by itself, would give rise to unstable hydrides. The x ratio between metal B and metal A number of atoms present in the crystalline structure can be 1/2, 1, 2 or 5, depending on the metal elements. One of the most important disadvantages is the weight of metal hydride system, that make it suitable only for stationary and some small portable application [22].

3.3.1. Thermodynamics functioning of metal hydrides

The main reaction that describes the storage and releasing, being a reversible reaction, of the hydrogen by using metal hydride is [22]:

$$AB_x + \frac{1}{2}nH_n \rightleftarrows AB_xH_n + \text{Heat} \tag{10}$$

Since the entropy of the hydride is lowered in comparison to the metal and the gaseous hydrogen phases separated, the hydride formation is exothermic and the reverse reaction of hydrogen release accordingly endothermic. Therefore, the reaction can be read by both senses and its direction is determined by temperature, pressure and reactants concentration (p-c-T) [19, 23, 24].

During the absorption process, first, the hydrogen molecules approach the metal surface through the Van der Waals force. Then, they start the formation of the hydrogen metal bond. At the end of this first step, the H atoms have to diffuse into the bulk to form M-H solid solution, commonly referred ad α-phase [23, 24]. In this phase, the concentration, given by the ratio between number of hydrogen (H) and metal atoms (M) ($c=\frac{H}{M}$), is very small. This is obtained by the Sievert's law, where the dependence of the concentration by the temperature and the hydrogen pressure is highlighted.

Then, the conversion from the saturated solution phase to the hydride phase takes place at constant pressure (plateau pressure). The plateau length represents the hydrogen quantity that can be reversibly stored in the metal, so, the lower the temperature the higher this amount is. The equilibrium pressure in the plateau directly depends by temperature, enthalpy and entropy variations through the Van't Hoff equation:

$$\ln \frac{p}{p_0} = \frac{\Delta H}{RT} - \frac{\Delta S}{R} \quad (11)$$

This equation explains the relation between pressure, hydrogen concentration and temperature, that is a characteristic property of the metal hydride material [19, 23, 24]. It has been experimentally demonstrated that the entropy variation depends almost entirely by the hydrogen dissociation value (from gaseous to solid form), This value is representative of the stability of the metallic bond between hosting metal and hydrogen. Hence the formation enthalpy can be estimated from the equilibrium temperature at the same pressure, that depends on the material involved [23].

After the complete conversion into the hydride phase, further dissolution of hydrogen take place as the pressure increases. Absorption and desorption processes and the relative thermodynamic aspects are described in a semi-logarithmic p-c-T diagram, where the isotherms of the hydrogen pressure are represented as a function of the concentration [19, 23, 24], as shown in the Figure 3.16. Further, If the logarithm of the plateau pressure is plotted as a function of 1/T, a straight line is obtained (Van't Hoff plot).

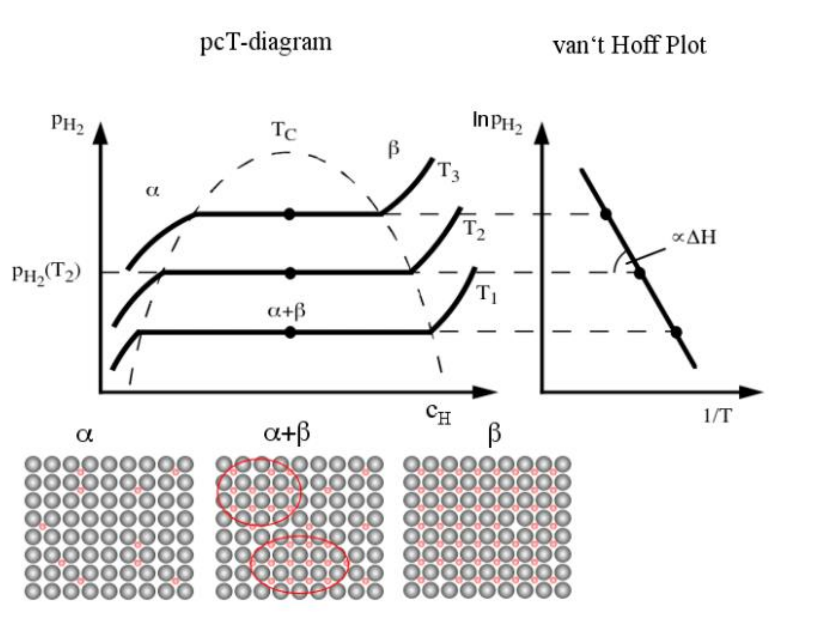

Figure 3.16. Schematic p-c-T diagram and Van't Hoff plot [Source: https://www.intechopen.com/chapters/21876].

In real thermodynamic condition, absorption and desorption processes do not show a flat plateau due to different losses, as: activation, decrepitation, hysteresis, plateau slope and gaseous impurity resistance. These losses generate an increasing of thermal energy needed to the desorption process and a decreasing in the opposite case. For this reason, a suitable thermal energy management is required.

From a kinetic point of view, generally, many room temperature hydrides have excellent intrinsic properties. Moreover, for stationary applications, it is somewhat less important because of relatively slow cycling of storage tanks.

3.3.2. Thermal management of metal hydrides

As said before, the hydrogen storage, through metal hydrides, is an exothermic and endothermic process, during charging and discharging phase respectively. Therefore, the heat generated through the exothermic reaction of charging process must be dissipated away from the metal hydrides to maintain the nominal condition of this phase and utilise the maximum storage capacity. Vice versa, the heat has to be supplied during endothermic reaction of hydrogen discharging in order to enhance or maintain the release rate of hydrogen. Therefore, a proper thermal management solution needs to be applied to achieve the desired performance of the overall system.

Metal hydrides thermal management using heat recovery from fuel cell is an idea to improve hydrogen discharging rate reducing the thermal energy required from an external heat source. In this case, through roughly estimation can be calculated the heat flux required by the storage tanks to release hydrogen, that at steady state is equal to:

$$\dot{Q}_{MH} = \dot{m}\,\Delta H \tag{12}$$

Where $\dot{Q}_{MH}$ is the required heat power needed to release a given hydrogen flow rate, represented by $\dot{m}$, with a given reaction enthalpy change ΔH of the dehydrating process, equal to the enthalpy of formation $\Delta_f H^0{}_{MH_x}$. On the other hand, the power lost $\dot{Q}_{FC}$, at the steady state conditions, by fuel cell as waste heat is equal to:

$$\dot{Q}_{FC} = (1-\eta)\,\dot{m}\,LHV \tag{13}$$

Where η is the fuel cell efficiency, in general equal to 50%, based on the hydrogen's lower heating value LHV (-241,8 kJ/mol). Therefore, the ratio between the two heat fluxes is equal to:

$$\frac{\dot{Q}_{MH}}{\dot{Q}_{FC}} = \frac{1}{(1-\eta)}\frac{\Delta H}{LHV} \tag{14}$$

Considering, for example, $LaNi_5$ with an enthalpy of formation $\Delta_f H^0{}_{MH_x} = -30{,}8\,\frac{kJ}{mol}$, then the heat flux needed to release hydrogen is around 25% of the total thermal power generated by the fuel cell [22].

However, the heat recovered from the FC stack can be used to supply other thermal demands, as for example domestic hot water, to improve overall energy efficiency of the system.

One of the proposed approaches, still largely under research, is to apply a latent heat Thermal Energy Storage unit (TES), based on Phase Change Materials (PCM), to store the heat generated during the hydrogenation reaction and reclaiming this heat for assisting the dehydrogenation reaction seems to be promising. The reason why this kind of system to manage thermal energy is quite important is due to high enthalpy change of the reversible chemical reactions of hydrogen and metal powder. Indeed, the heat generated and required by the MH storage system during charging and discharging, respectively, are significant, accounting for around 10–20% of the total chemical energy of the hydrogen stored in the tank, that represents an important loss for the overall system. By using PCM as thermal energy management device, it has been found, by simulation over a whole year, that the amount of energy stored by the charging process equals that is required in the discharging process, equivalent to approximately 12% of the total yearly energy content of hydrogen (based HHV) generated by the electrolyser [25].

3.3.3. Regulation for hydrogen storage installation in the residential environment.

As concern the hydrogen storage into fixed tanks, the Italian regulation does not provide a specific rule for hydrogen. However, considering that the hydrogen is a flammable gas, it is possible to refer to the regulation concerning the flammable gas deposits in fixed tanks [26]. According to this arrangement, the maximum storable geometrical capability without restrictions is 750 l. A storable geometrical capability higher than this value involves in technical specification for the design, construction and installation to be approved by the firefighter. For this reason, considering the application in the residential sector in close time, it seems reasonable to limit the maximum storable geometrical capability to 750 l, looking forward for a hydrogen dedicated regulation. Although this introduces limitations in hydrogen storage capabilities, this limit was imposed to be compliant to the existing regulation. This allows direct application of the obtained results for the proposed system with hydrogen storage.

3.4. Combined Heat and Power Internal Combustion Engine technology

The Internal Combustion Engine (ICE), shown in the Figure 3.17., is an alternative volumetric machine, in which the combustion of a certain amount of fluid occurs (fuel-air mixture) inside the combustion chamber [27]. In general, the combustion reaction can be expressed through the reaction (15):

$$C_nH_m + \left(n + \frac{m}{4}\right) O_2 + \frac{79}{21}\left(n + \frac{m}{4}\right) N_2 \rightleftarrows n * CO_2 + \frac{m}{2} H_2O + \frac{79}{21}\left(n + \frac{m}{4}\right) N_2 \tag{15}$$

Afterwards the combustion, the chemical energy of the fuel is transformed into thermal energy. This thermal energy generates the fluid expansion that pushes the piston, generating mechanical energy. The piston is then connected to a crankshaft that transform the linear motion of the piston into the rotary motion of the crankshaft itself. At the end, the mechanical work of the crankshaft is then converted into electrical energy through a generator. However, generally, the percentage of chemical energy that is converted into the electrical one represents a low percentage, due to thermodynamic and mechanical losses. However, the advantage of engines in stationary applications depends on the possibility to recover the waste thermal energy contained in the exhaust gas and cooling systems, which generally represents a high percentage of the inlet fuel energy [27, 28]. Therefore, the generation of both electrical and thermal energy by the ICE in the stationary application is the so-called Combined heat and Power (CHP). However, this topic is further discussed later [Chapter 4.].

Indeed, in this chapter, only a brief classification and description of the ICEs is reported. Further, all the generated losses, considering the conversion from the chemical energy to the electrical one, are analysed. At the end, since in the considered application the produced fuel by the electrolyser is the hydrogen, some examples of hydrogen ICEs are reported.

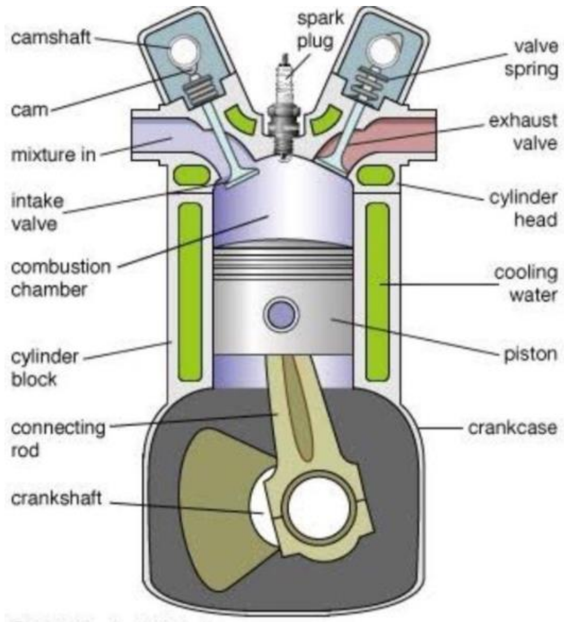

Figure 3.17. Representation of an Internal Combustion Engine [Source: https://www.slideshare.net/rrgsb/automo-lesson3].

3.4.1. Brief classification, description and estimation of the efficiency

The ICE can be mainly classified into two categories: the spark ignition engine, in which a pre-mixed and dosed air-fuel mixture, with a stochiometric ratio, is ignited by a spark plug, and the compression ignition engines, in which the introduced air into the cylinder is compressed to high pressure, raising its temperature to the auto-ignition temperature of the fuel, that is injected at high pressure.

They can also be classified considering the different operating cycle (2 or 4-stroke), composed by intake, compression, combustion-expansion and exhaust, as follow: four-stroke engine, in which the operating cycle occurs every two turns of the crank, and each of its phases is distinct from the others, and the two-stroke engine, in which the operating cycle occurs every turn of the crank.

Further, ICEs can be distinguished considering the different fuel supply system, that are: the carburettor, the indirect injection and the direct one [27, 29].

As concern the working phases, they can also be represented by thermodynamic cycles: the Otto cycle, for the spark ignition engines, the ideal Diesel cycle, for the compression ignition engines, the ideal Sabathé cycle, for the controlled ignition engines. Each of these cycles is characterized by an ideal efficiency (η_{id}), considering both an ideal machine and an ideal fluid [27, 28].

However, moving from the ideal fluid to the real one, the most important differences are represented by the variation of the specific heat c_p and c_v as a function of the temperature, that generates a higher subtraction of heat with respect the ideal case, and the phenomenon of chemical dissociation, that occurs in the combustion reaction if the temperature is higher than 2000 K and the air-fuel mixture is the rich one ($\alpha > \alpha_{st}$). Thus, considering these losses, each of the above-mentioned cycles is characterized by a limit efficiency (η_{lim}).

At the end, both the real machine and the real fluid are considered, generating the following losses: the fluid-wall heat exchange, the pressure losses in the intake and exhaust pipes, the imperfect combustion and the real valve timing. Thus, considering these further losses, each of the above-mentioned cycle is characterized by a thermo-fluid dynamics efficiency ($\eta_{\theta i}$).

Then, the indicated efficiency (η_i) is obtained as the product of the limit and thermo-fluid dynamics efficiencies [27, 28].

In addition to the thermodynamic losses, mechanical ones must also to be considered. These are generated by the mechanical frictions, i.e. the frictions in all couplings of crank due to gas pressure loads, the frictions of the inertia forces due to the rotating masses, the frictions of the sealing segments and due to dragging of auxiliary accessories and the frictions due to the replacement of the fluid. Thus, these losses are considered in the organic efficiency (η_o).

Therefore, the chemical energy that is converted into mechanical one is represented by the useful efficiency (η_u), that corresponds to the product of the indicated and organic efficiencies. This parameter ranges from 30% to 46%, depending on different design condition [28, 29].

However, as said in the introduction of this technology, the biggest amount of the losses in an ICE are represented by thermal energy contained into the exhaust gas and the cooling systems. This energy, that ranges from 60% to 70% of the inlet fuel energy can be recovered and used for other purposes [28, 29].

3.4.2. Hydrogen ICE

There are several important characteristics of hydrogen that greatly influence the development of this kind of technology:

- Wide range of flammability. Compared to nearly all other fuels, hydrogen has a wide flammability range (4-74% versus 1.4-7.6% volume in air for gasoline). This first leads to obvious concerns over the safe handling of hydrogen. But, it also implies that a wide range of fuel-air mixtures, including a lean mix of fuel to air. Running an engine on a lean mix generally allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of critical pollutants such as nitrous oxides (NO_X).
- Low Ignition Energy. The amount of energy needed to ignite hydrogen is on the order of a magnitude lower than that needed to ignite gasoline (0.02 MJ for hydrogen versus 0.2 MJ for gasoline). On the upside, this ensures ignition of lean mixtures and allows for prompt ignition. On the downside, it implies that there is the danger of hot gases or hot spots on the cylinder igniting the fuel, leading to issues with premature ignition and flashback (i.e., ignition after the vehicle is turned off).
- High Flame Speed. Hydrogen burns with a high flame speed, allowing for hydrogen engines to approach the thermodynamically ideal engine cycle (most efficient fuel power ratio) when the stoichiometric fuel mix is used more closely. However, when the engine is running lean to improve fuel economy, flame speed slows significantly.
- High Diffusivity. Hydrogen disperses quickly into air, allowing for a more uniform fuel/air mixture, and a decreased likelihood of major safety issues from hydrogen leaks.
- Low Density. The most important implication of hydrogen's low density is that without significant compression or conversion of hydrogen to a liquid, a very large volume may be necessary to store enough hydrogen to provide an adequate autonomy or driving range (for cars). Low density also implies that the fuel-air mixture has low energy density, which tends to reduce the power output of the engine. Thus, when a hydrogen engine is run lean, issues with inadequate power may arise.

Based on the above unique properties of hydrogen, there are several relevant tradeoffs pertinent to the use of hydrogen ICE. Instead, as concern the comparison with the other technologies, hydrogen ICE electric generator tends to fall in a middle ground between the higher efficiency hydrogen FC (H-FC) and the standard ICE. Indeed, it reaches an electrical efficiency equal to around 40%. Further, it presents lower costs than the hydrogen FC, although they are higher than in the case of standard ICE. Instead, it presents lower pollutant emissions than the standard ICE while slightly higher than the hydrogen FC [30].

Therefore, the use of hydrogen ICE could generate a disadvantage as concern the efficiency of the storage system, while, on the other hand, it could generate an advantage as concern the cost of the plant.

However, currently this kind of technology is mainly applied in automotive sector. Instead, as concern the stationary application, it presents design sizes not applicable in the residential sector considered in this thesis.

An example is represented by the agenitor H_2 realized by 2G. This is a hydrogen CHP ICE able to work with 100% of green hydrogen, highly efficient and more robust and cheaper than FC [31]. However, the minimum commercialized size for this kind of technology is equal to 75 kW.

For this reason, the analysis is carried out under the hypothesis that in the future this kind of technology will reach a design size suitable to be applied in the contest of the hydrogen-based system for the residential sector.

4. Polygeneration concept and considered polygeneration systems

The concept of energy polygeneration, or simply polygeneration, is quite new and it has been introduced thanks to the advancement of energy technologies. This is explained in this chapter and why the proposed systems are considered as polygenerative plants is discussed. To do this, it is needed to firstly define the basic concepts of cogeneration, i.e. a plant that maximizes the conversion efficiency of a primary energy source, usually a fuel, into two or more useful energy forms.

Thus, to introduce this concept in relation with the considered plants, the different pathways that have been analysed to store the electrical energy generated by the PV plant and their brief descriptions have to be considered. Starting to consider each involved technology and the corresponding electrical round-trip efficiency, it is possible to affirm, by roughly estimation, that the hydrogen pathways have no chance to compete with the battery. Indeed, the hydrogen-based system presents an electrical round-trip efficiency equals to around 60% for the electrolyser, 50% for the fuel cell or 30% for the internal combustion engine. Therefore, the corresponding electrical efficiency of the system is equal to around 30% in the case of FC or 18% in the case of ICE. While, in the second case, considering the lithium-ion battery, the electrical round-trip efficiency is equal to around 90%. However, it is important to notice from the previous chapter that both the electrolyser, fuel cell and internal combustion engine involve exothermic processes during their functioning, generating heat. Thus, if this thermal energy is recovered and used for other purpose, the overall efficiency of the system increases, giving the hydrogen storage the possibility to be competitive with respect to the battery one.

The concept to recover heat, or in general other useful gain, from a single source is usually named polygeneration. This kind of systems are one of the key for the reduction of the human impact on the environment because reduce the consumption of primary energy, so that they are increasingly studied.

4.1. Combined heat and power (CHP) and polygeneration concept

Combined heat and power (CHP), also known as cogeneration, is defined as the generation of heat and power from a single fuel source [32, 33, 34, 35, 36]. Indeed, considering a typical CHP system configuration, the fuel is supplied to a prime mover technology to produce electrical power. In this process waste heat is produced according to the specific prime mover that is used. If this thermal energy is recovered and used there is an increase of the total energy conversion efficiency, i.e. a reduction of costs and pollution. By this approach, system efficiency can be elevated from as low as 20% to over 90%, depending on the prime mover technology and the extent of the waste heat utilisation [32, 34, 35, 36], as shown in the Figure 4.1 for residential applications, where this results in a significant reduction of primary energy demand, GHG emission and running cost for the consumers [32, 34, 35]. CHP is largely used in industry since long time, but conventional industrial systems are not so suitable for small residential application mainly because noisy, but also because in small scale the ratio cost benefit is not competitive.

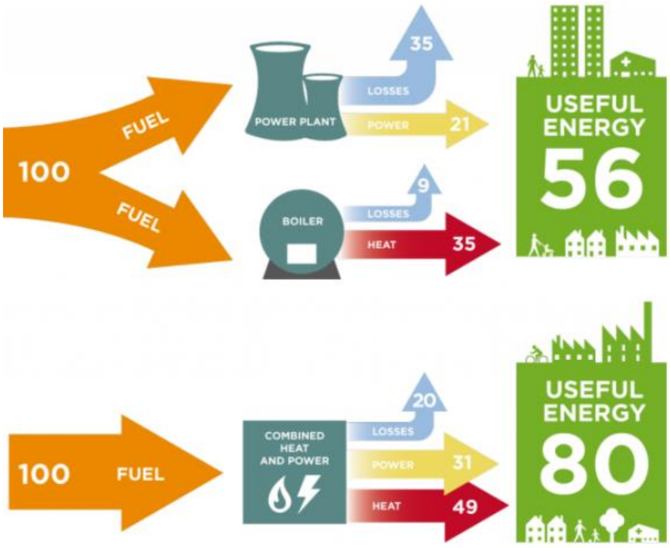

Figure 4.1. Traditional versus CHP system energy flows [Source: https://ukdiss.com/examples/chp-plant-contribution-uk-energy-use.php].

More recently the CHP concept was enlarged to tri-generation, or combined cooling heat and power (CCHP) if the recovered waste heat is used to produce useful cooling through a heat driven cooling technology. This was possible thanks to the development of adsorption heat pumps that can use waste heat for cooling down air or water [32, 33].

A generalisation of these concepts is the polygeneration system, that correspond to an energy supply system which delivers simultaneously more than one form of energy to the final user from a single primary energy resource [33, 35, 37, 38]. This kind of system presents all the pre mentioned advantages of the previous system but is not limited to electric energy and thermic energy (heat and cooling). A further generalisation of the concept is to consider also the production (generation) of a product that could be fuel or raw material for other processes [37, 38, 39], hydrogen is one of these. This because hydrogen is a fuel that can be used also for an ICE generating mechanical energy, and waste heat, or as raw material for chemical plants, refineries and some food industries. According to this vision, application of renewable energy storage by hydrogen (green hydrogen) in distributed generation applications is an example of polygeneration system [40]. Finally, this concept was proposed for hospitals, a PV based system able to supply power (electric and thermic), oxygen and other services, using hydrogen as intermediate [39].

In this thesis, it is considered the application of this concept to the case of energy communities composed just by families. For first evaluation of the system just electric power and heat was considered to allow a simple comparison of the hydrogen-based system in respect to the current technologies and looking to the future for a more comprehensive analysis including cooling and/or car refuelling.

4.2. Description of the hydrogen storage as a polygeneration system

Once the general concept of polygeneration has been defined, it is possible to give a more accurate description of the considered renewable polygeneration energy plants. As reported in chapter 3, two cases of hydrogen utilisation have been analysed: the first one involves the FC, that refers to the Figure 3.3 (Page 14), and the second one involves the ICE, that refers to the Figure 3.4. (Page 14).

Indeed, now it is known that the thermal energy from the electrolyser, fuel cell and internal combustion engine through the appropriate thermal management system can be recovered and considered as a useful gain for the system.

Thus, starting from a single input, that in this case is represented by the solar radiation generating electricity through the PV plant, it is possible to generate multiple outputs. Firstly, the electrical energy generated during the day is used to satisfy the electrical load required by the end users. However, the exceeding amount of energy is used to generate hydrogen by the electrolyser, generating at the same time thermal energy. Then, H_2 is absorbed by the metal hydrides tank when generated and desorbed, for supply FC or ICE, when the electrical energy from the users is required. At the end, the hydrogen is used as fuel to feed the FC or ICE to obtain electricity on demand and generating simultaneously heat. For the way in which the plants are considered, it is possible to say that the outputs of the system are the thermal energy generated from the electrolyser and the electrical and thermal one obtained from the FC/ICE, Figure 4.2 reports a simple scheme. Here, the control volume is used to consider PV system with the hydrogen storage as a black box. This is applied to highlight the incoming and outcoming energy flows of the system.

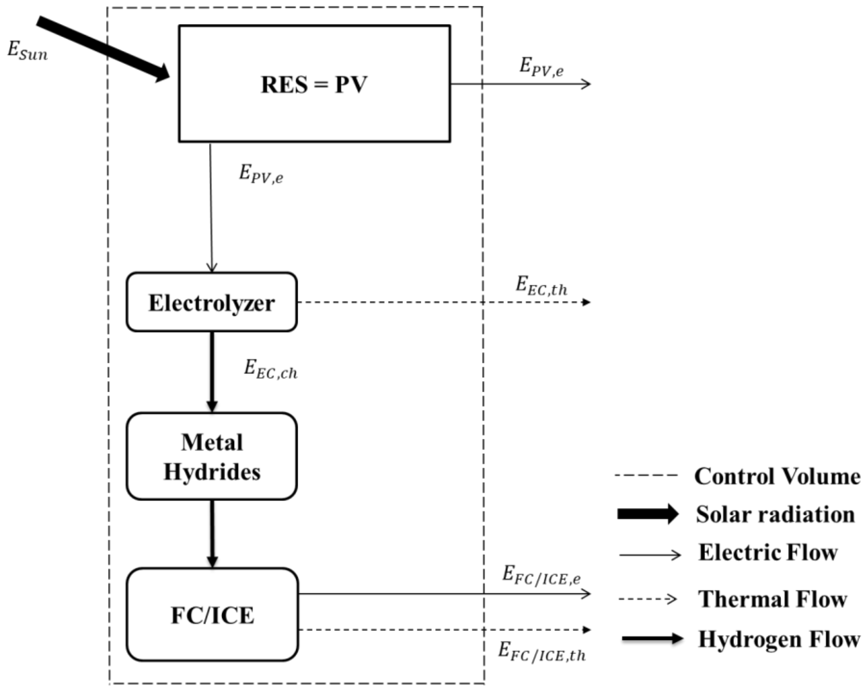

Figure 4.2. Scheme of the input and output energy flows.

To notice that metal hydrides warm up in absorbing phase and cooling down in desorbing phase, for this reason in literature metal hydride heat pumps have been proposed [41]. However, we not considered this possibility due to the complexity of the system and the necessity to have a hydrogen storage able to follow the electrolyser and the FC/ICE requests and not the end user necessities.

Once the energy flows of the plant and the possible recovered thermal energy are established, it is important to evaluate how to use these.

4.3. Application of the hydrogen storage as polygeneration system

In the previous paragraph the energy flows and the possibility to recover the thermal energy by the applied devices in the hydrogen systems have been defined. Instead, in this paragraph it is explained how it is possible to recover this generated heat.

In general, heat can be converted back to electricity, mechanical power, or additional heat for use in targeted functions allowing for energy-saving. The viability and limitations of water heat recovery for a particular system depend on the temperature of the waste heat source. Thus, the temperature of the waste heat is the main factor that determines the possible exploiting routes of it. Accordingly, waste heat is normally classified into high, medium and low-grade heat corresponding to the temperature level higher than 400°C, 100-400°C, and lower than 100°C, respectively. Generally, the higher the temperature of the waste heat, the better its quality, consequently the efficiency, and the easier to be retrieved. While, recovering low-grade heat is more challenging and less feasible than recovering high and medium grade heat [42].

Therefore, knowing the temperature of the recovered heat it is possible to decide its application according to the following:

- The PEMFC works at low temperature, around 60-90 °C. In general, it is cooled from water flow that passes through a heat exchanger. The cooling fluid reaches a temperature at around 45-70°C, from which is possible to recover heat [43].
- The AEMEC works at a temperature around 55°C. If the liquid-cooled version is applied, the electrolyser is equipped with a liquid-liquid heat exchanger, where a cooling liquid flow is used to maintain the device at the operating temperature. Therefore, from this it is possible to recover a given amount of heat, though the quality of heat obtainable is limited at the operating temperature of the electrolyte [44].
- The gases in the ICE can reach around 2000°C after the combustion. However, the exhaust gases that immediately leave the engine can have temperature from 450 to 600 °C [45], while the liquid coolant works at a temperature close to 100 °C.

Thus, from both the considered fuel cell and the electrolyser is possible to recover low-grade thermal energy, while from the engine is possible to recover high-grade heat from the exhaust gases and low-medium-grade heat from the cooling liquid.

Despite the low temperatures of the generated heat by the FC and EC, all of them are suitable to be used as CHP in the residential sector, since low temperature applications are involved, as space heating or domestic hot water. In this specific case, it has been thought to match the recovered thermal energy with the solar water heating plant, for the DHW production [42, 43, 46, 47, 48]. Indeed, the DHW has to reach a temperature around 40-50 °C to satisfy the requirement of the end users. Because of the recovered thermal energy, the use of the auxiliary boiler decreases. This means that a smaller amount of fuel is burned, generating an energy and GHG emission saving.

Once the way in which the thermal energy is recovered, the final versions of the schemes of the plants are shown in the Figure 4.3. and 4.4., respectively for the case with FC and with ICE. Here both the electrical, hydrogen and thermal flows are represented.

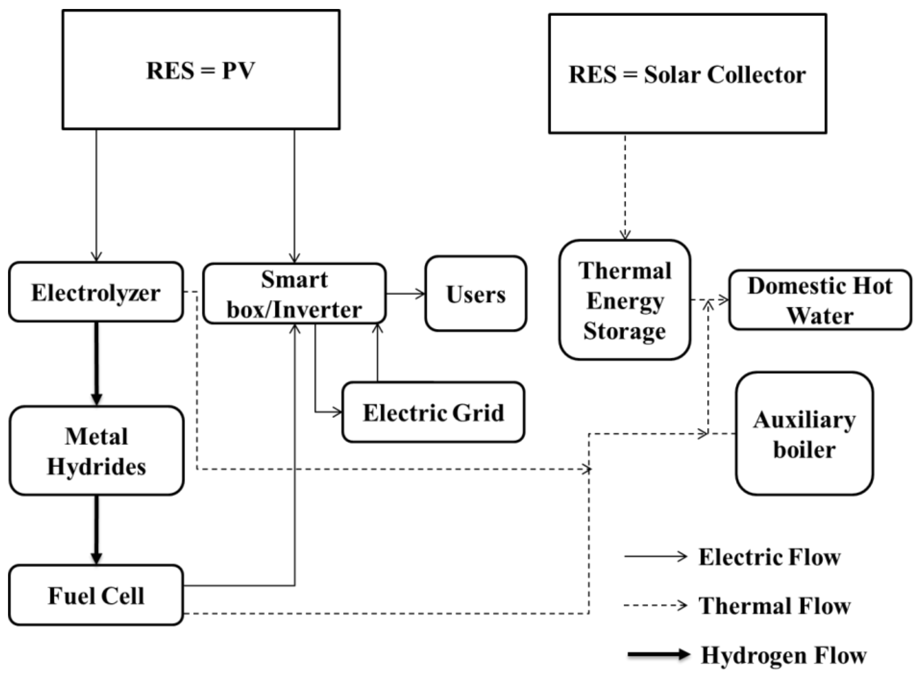

Figure 4.3. Photovoltaic plant with FC and the possibility to recover thermal energy.

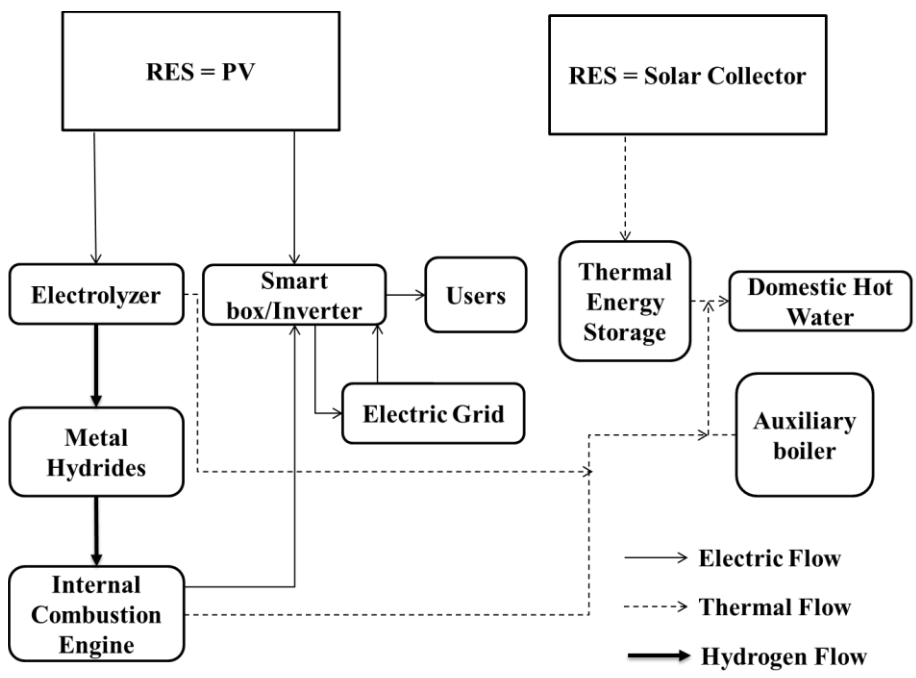

Figure 4.4. Photovoltaic plant with ICE and the possibility to recover thermal energy.

4.4. Cogeneration efficiency

The aim of this paragraph is to make an estimation of the cogeneration efficiency for hydrogen-based system and to compare it with the electrical one. First, to calculate the overall efficiency is important to establish control volume of the system. Indeed, the interest is now focused on calculating the performance of the energy storage systems, therefore, it has to be considered as a black box. In this way, it is possible to properly apply the energy balance, in order to calculate the cogeneration efficiency, given by the following equation:

$$\eta_{cogeneration} = \frac{E_{out} + Q_{out}}{E_{in}} \tag{16}$$

Where $\eta_{cogeneration}$ is the cogeneration efficiency, E_{out} is the amount of output electrical energy, Q_{out} is the amount of output thermal energy and E_{in} is the amount of input electrical energy. Then, the incoming electrical energy from the PV plant has been assumed equal to 1 kWh. Furthermore, also the (η_e) electrical and (η_{th}) thermal efficiency of each component has to be considered, which are listed below:

- The PEMFC has a η_e=50% and η_{th}=50%, based on the HHV.
- The AEMEC has a η_e=60% and η_{th}=20%, based on the LHV [43].
- The ICE has a η_e=30% and η_{th}=60%, based on the LHV.

Now, it possible to know the incoming and outcoming energy flows and to make the energy balance needed to estimate the efficiencies of the systems, as represented in the Figure 4.5. and 4.6.

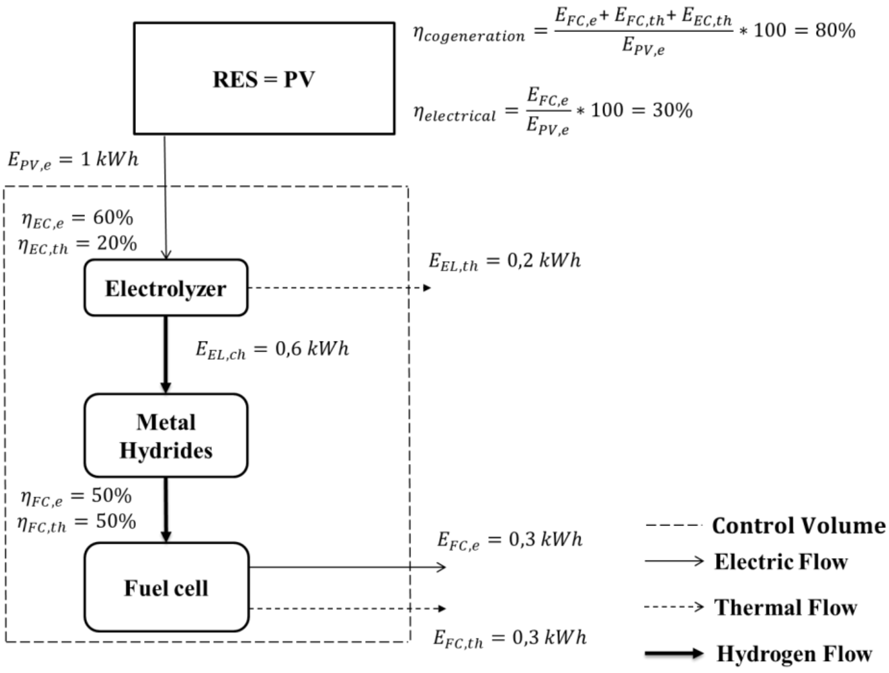

Figure 4.5. Efficiencies of the hydrogen system with FC.

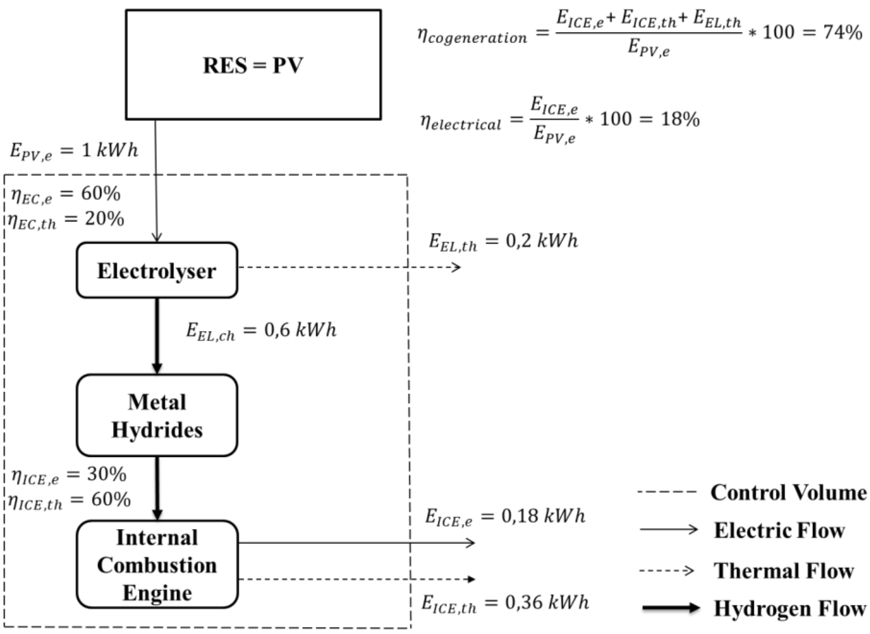

Figure 4.6. Efficiencies of the hydrogen storage with ICE.

By using metal hydride hydrogen storage, the efficiency of the storage is close to 100%. This because none compression is requested for hydrogen storage. Hydrides can be charged at the electrolyser output pressure.

With these assumptions, the hydrogen storage with the FC presents a cogeneration efficiency equal to around 80% while the hydrogen storage with the ICE presents a cogeneration efficiency equal to 74%.

4.5. Hydrogen storage system versus battery

In the previous paragraph, the cogeneration efficiency applying hydrogen has been estimated, resulting in a significant increase with respect to the simple electrical efficiency. This could make the hydrogen storage competitive with respect to the battery, although the efficiency is even lower. Indeed, the metal hydrides present some characteristics advantages with respect the batteries [50], which are shown below:

- Self-discharge: metal hydrides do not undergo self-discharge and can store their charge indefinitely. For this reason, it is possible to design the size of metal hydrides to store the excess of hydrogen production during the summer, to use this during the winter. On the contrary, all batteries steadily lose charge over time. For example, self-discharge rate of Li-ion is as high as the temperature and SOC are higher, in general a value around 3-5% a month. Therefore, it is not possible to create a seasonal storage of energy.
- Safety: Li-ion battery suffer from lithium dendrite formation which may lead to short-circuit of the battery. Further, the organic electrolyte is hazardous in the presence of an oxidizing agent, which may result in runaway reactions and the battery catching fire or exploding. Instead, concerning the metal hydrides, during a severe tank rapture during the desorption process only hydrogen in gaseous phase will be instantly released in the environment, since the desorption is immediately stopped. In fact, during normal operation, the pressure inside the reaction bed is slightly depressurized to ~0.5 [bar] and now the powder is exposed to the ambient pressure, decreasing the most important driving force (Δp); moreover, the heat supply ceases suddenly, so, as conclusion, hydrogen explosion is very unlikely. Safety problem usually centres around pyrophoricity (the tendency for a hydride powder to burn when suddenly exposed to air) and toxicity, resulting from an accidental ingestion or inhalation of powders in case of accident.
- Deep discharge: unlike rechargeable batteries, metal hydride systems do not suffer capacity loss from being fully discharged.
- Longevity: a battery's cycle life is defined as the number of cycles until the capacity reaches 80% of its initial reversible value. Commonly, Li-ion batteries have a cycle life between 1000 and 4500 cycles, therefore, a lifetime between 7 and 20 years. Li-ion batteries with a 95% retention after 30,000 cycles have been discovered, however, at the expense of energy density, which is a severe drawback. In comparison, the metal blend LaNi5 showed no capacity loss over 3300 cycles when using a H_2 purity above 99.9999%. Furthermore, TiFe0.8Ni0.2 showed only a 16% capacity loss after 65,000 cycles, equivalent to a ~178 year product lifetime based on a daily cycling regime. The biggest issue so far for the metal hydrides is the reversibility and cyclic stability and much less long-term cycling has been performed.
- System size: as the energy density, by volume, of metal hydrides is much higher than for Li-ion batteries, the system size of a stationary energy storage system will be much denser.

Therefore, considering all the differences between the two applied technologies and the possibility that the hydrogen storage could become competitive with respect the battery, it has been deemed reasonable to carry out a more detailed energy balance analysis. To do this, in the following chapter have been reported all the considerations and the procedures to obtain the suitable results in terms of performances.

5. Energy balance on annual base of reference home systems.

In this chapter is carried out the energy balance on annual average of the considered power plants in the residential sector. In this way, it is possible to properly design the storage system, with the aim of maximizing the self-consumption of the produced EE by the PV plant. Further, a more detailed performance parameters of the overall system are obtained to have a better comparison of them.

To this purpose, a residential building, located in Italy, has been considered. This is composed by ten flats and, therefore, inhabited by ten families, compounded by 3-4 members.

The average Italian family consumes about 2618 kWh of EE for one year, of which about 1/3 during the day (light hours) and 2/3 during the night [51], as shown in the Figure 5.1. While it requires about 6000 kWh of TE per year for the DHW production, with symilar distribution of the consumption during the day [17].

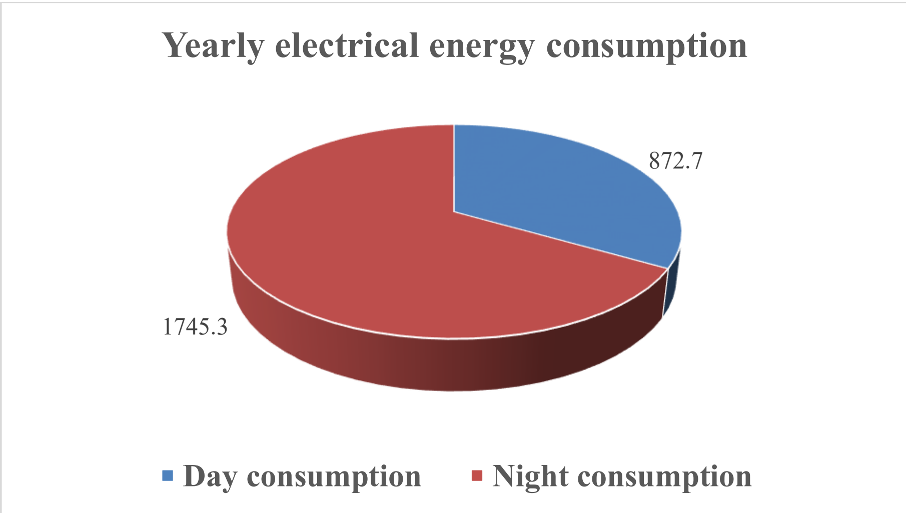

Figure 5.1. Yearly EE consumption by an average Italian family.

Instead, as concern the characteristics of the electrical production plant, the PV specific annual energy production (kWh/kW_p) has to be considered as a function of the peak power of the plant. For this reason, a sensitivity analysis is carried out, in a range from 20 kW_p to 40 kW_p. Further, as said in the Chapter 3, the PV specific annual energy depends on the annual irradiance and, therefore, on the considered location [52]. Further, the PV monthly energy production depends on the period of the year. The maximum production is achieved during the summer period, while the minimum one during the winter. Considering the PV hourly energy production, it is a function of the solar height with respect the plant itself. Therefore, it reaches the maximum production during the solar noon, period of the day that coincides with the lowest electrical energy consumption from the users. This means that, on average, an excess of energy production is expected during the light hours, as shown in the Figure 3.1. [Page 12], an energy usually exported to the grid.

As a consequence, the battery or hydrogen systems have been designed to be able to store the exceeding amount of EE (E_{ss}) during the day, reducing the exported energy to the grid. At the same time, the stored energy is used during the night, decreasing the amount of energy to be imported from the grid.

As concern the design of the storage devices the most important output parameter is the system size. Considering the battery, this is defined by the capacity, that is the amount of energy that is possible to store and discharge. However, as said in the previous paragraphs, the battery is affected by the DOD, which represents a loss of energy storage capacity. This phenomenon limits the device to work between an upper (SOC_{max}) and a lower (SOC_{min}) level of the capacity, given respectively by the Equations (3) and (4) (Page 22 and 23). Therefore, to work with the desired amount of energy, the battery size has to be designed taking into account this parameter.

While, considering the hydrogen system, the size is defined as the electrolyser nominal power consumption ($P_{EC,e}$), that represents the amount of power that is needed to obtain a certain amount of hydrogen. For this specific application, this value is considered equal 2,4 kW for each module, with a corresponding hydrogen production of 0,045 kg/h [44]. The metal hydrides tank and the FC/hydrogen ICE are designed on the base of the electrolyser size. Considering the first one, the characteristic design parameter is the geometrical volume, that represents the occupied external volume. To the purpose of the analysis, this is equal to the upper limit of 750 l (Page 33), thus with a hydrogen storage capability of 27,72 kg. In this way, the metal hydrides tank could result oversized considering the average annual balance. Indeed, in each analysis the minimum acceptable geometrical volume to satisfy the hydrogen production is reported. However, the maximum hydrogen storage capability is considered, despite the cost it can entail. Indeed, this allows the possibility to consider the seasonal hydrogen storage and, consequently, the possibility to increase the energy supplied to the users. This will be following analyzed in the Chapter 6. Further, unlike the battery, the size of this device is not affected by the DOD phenomenon. This means that the metal hydrides tank can be fully filled ($SOC_{max} = 100\%$) and emptied ($SOC_{min} = 0\%$) of hydrogen. As concern the FC/hydrogen ICE, they are designed on the base of the energy that has to be able to deliver at a given period of time. Therefore, to achieve this design parameter, it is believed that these devices must be able to produce the maximum production of energy during the time of year that has fewer night hours.

Therefore, the first goal of the analysis is to carry out a proper design of the storage systems, with the purpose that they meet the requirements.

While, as concern the design of thermal production plant, the SWH system is considered constant and is composed by 40 m^2 of collector area and 2000 l of water storage tank volume. With these design features, the percentage of covered TE by the solar water heating varies from a value between 50% to 60% of the energy required by the end users, depending on the annual irradiance and, therefore, on the location, as in the case of the PV energy production. [17]

For this reason, the analysis is also carried out considering three different Italian cities. Therefore, at each of them corresponds a different performance of the renewable technologies [52], as reported in the Table 5.1.

Table 5.1. Summary of the energy performance in the considered Italian cities.

Location	Milan	Rome	Syracuse	
Latitude	45°28'	41°54	37°5'	[-]
Longitude	9°11'	12°28'	15°16'	[-]
PSH	4,63	5,29	5,5	[-]
PV specific daily energy production	3,42	4,07	4,28	[kWh/kW$_p$]
Covered thermal energy by the SWH plant	50	55	60	[%]

This variable gives the possibility to make a sensitivity analysis useful to compare how the solar technologies perform considering cities placed in different environmental condition at the different installed PV powers.

Once the input data have been listened, the model to obtain the energy balance and design the PV plant with the different storage systems is described. Then, this is used to simulate the functioning of the system with the different variable input date and to obtain the results of the performance.

5.1. Energy balance, design of the storage system and main parameters

First, the aim of this paragraph is to illustrate all the possible energy flows between the RES, the storage system, the users and the grid or the auxiliary boiler. Then, the main point to address is the definition of the storage system size, according to the aforementioned goals, i.e. the maximization of the EE supplied to the users. To do this, it is needed to both maximize the self-consumption and minimize the exchange of power with the grid. Further, the way in which the main performance parameters of the system are obtained is defined.

Thus, starting from the first goal, the daily energy balances of both the electrical and thermal system are analysed. These mainly depends on the daily produced EE by the PV plant ($E_{PV,e}$) and the produced TE by SWH system (E_{SWH}) and on both the daily required electrical and the thermal energy by the users (respectively E_e and E_t). Indeed, the situations that can occur depend on the different level of produced and required daily energy. Further, they also depend on the considered period of the day. Indeed, the analysis is divided into two parts, considering the day and the night.

To do this, as concern the EE balance, the daily average consumed EE (E_e) is splitted that consumed during the day ($E_{e,d}$) and that consumed during the night ($E_{e,n}$), considering the proper proportions.

Therefore, as concern the different situations that can occur during the day, three possible energy flows can be identified:

- $E_{PV,e} - E_{e,d} < 0 = E_{d,d}$, in this case $E_{d,d}$ represents the EE deficit during the day, that has to be imported from the storage system and/or from the grid ($E_{i,g}$). The three different situations that can occur in the case of EE deficit during the day are represented in the Figure 5.2., Figure 5.3. and Figure 5.4.

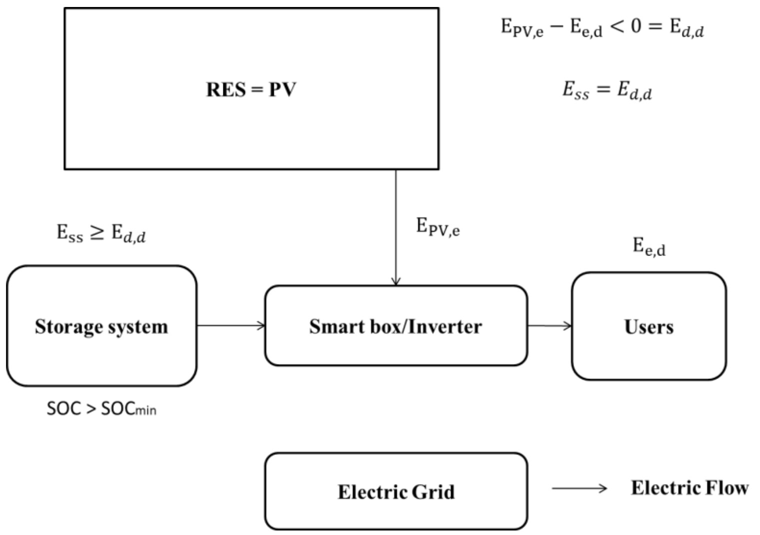

Figure 5.2. EE deficit during the day totally covered by the storage system.

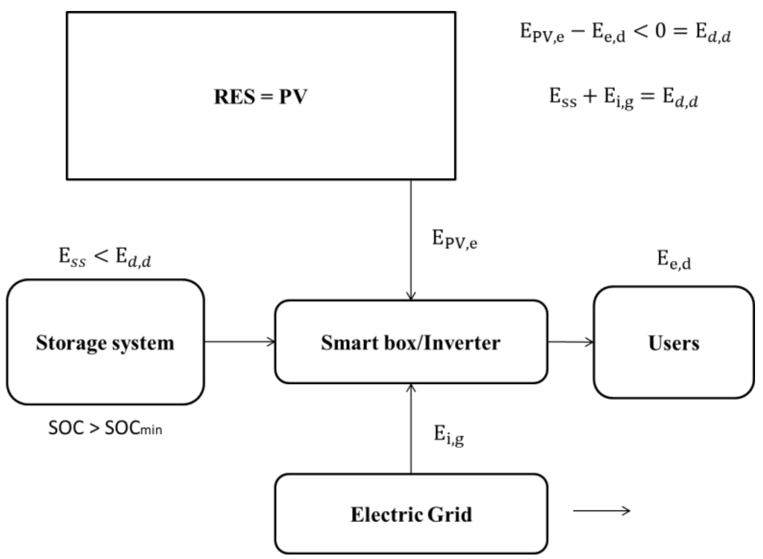

Figure 5.3. EE deficit during the day covered both by the storage system and the grid.

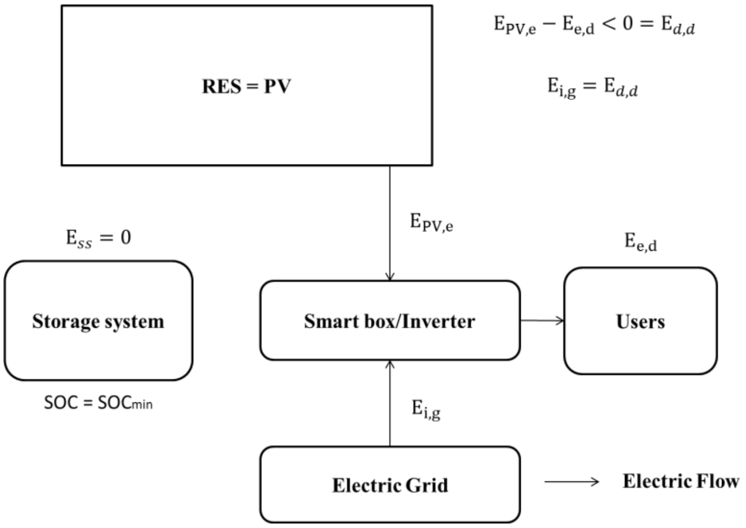

Figure 5.4. EE deficit during the day totally covered by the grid.

The first two pictures represent the situations in which in the previous days the PV energy production has been higher than the required one during the day, allowing the storage of a certain amount of EE. In turn, if this amount of stored energy has been higher than the required one during the night, a reserve of energy ($E_{ss,r}$) is generated and released in the following cloudy days, when the PV production is lower. In the case of the battery this has to be released in a short period of time, because this device suffers of self-discharge. While in the case of hydrogen storage system this can be released in a medium-long period of time because this storage system does not suffer this phenomenon, as said in the previous chapter. The last picture represents the situation in which the $SOC = SOC_{min}$, therefore there is not the possibility to release EE from the storage system. Therefore, the EE deficit has to be totally covered by the energy imported from the grid.

- $E_{PV,e} - E_{e,d} = 0$, in this case the produced EE is equal to the required one. This means that there is not the possibility to store EE but at the same time there is not energy needing from the grid.
- $E_{PV,e} - E_{e,d} > 0 = E_s$, in this case E_s represents the EE surplus during the day, that has to be stored into the storage system (E_{ss}), battery and/or exported to the grid ($E_{e,g}$). Also in this case, three possible scenarios can occur and are represented in the Figure 5.5., Figure 5.6. and Figure 5.7.

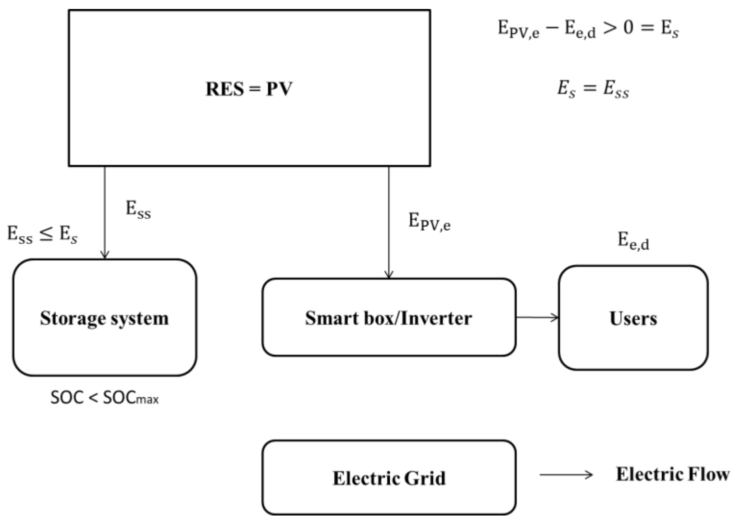

Figure 5.5. EE surplus during the day totally stored.

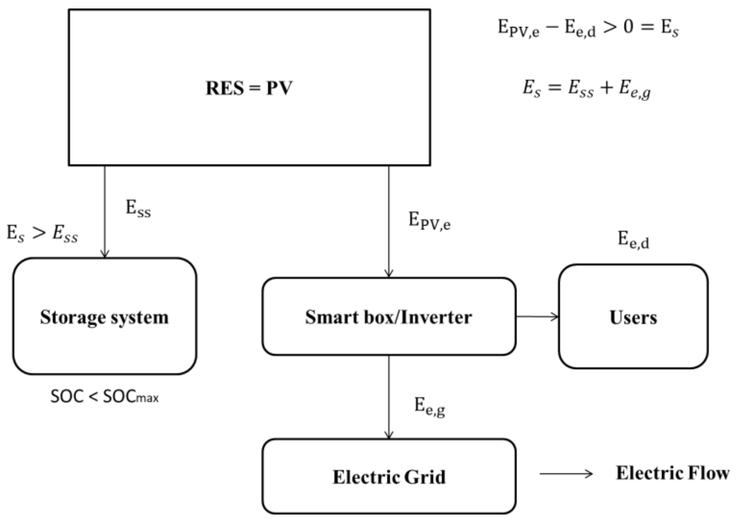

Figure 5.6. EE surplus during the day both stored and exported to the grid.

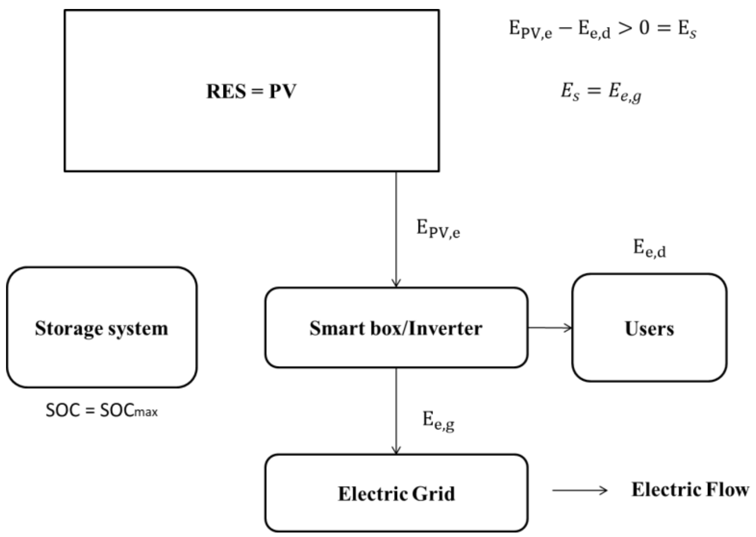

Figure 5.7. EE surplus totally exported to the grid.

The first picture represents the situation in which the energy surplus can be totally stored as the SOC $\leq SOC_{max}$. The second one represents the situation in which the energy surplus is partially stored, until the SOC becomes equal to SOC_{max}, and then exported to the grid. The third represents the situation in which the storage system is already totally filled and therefore all the energy surplus has to be exported to the grid. This is the situation of the saturation of the storage system and will be analyzed in detail in Chapter 6.

As concern the design of the storage system, once the aim is to maximize the self-consumption of produced EE supplied to the users, it has to be able to store all the average exceeding amount of EE by the PV production with respect the average energy consumption during the day on annual base. In this way, the amount of exported energy during the day has not to be considered, while the amount of energy imported from the grid during the night is reduced. Therefore, the following equation is applied:

$$E_{ss,max} = E_{PV,e,a} - E_{c,d,a} \tag{17}$$

Where $E_{ss,max}$ is the maximum storable energy, $E_{PV,e,a}$ is the average daily produced EE and $E_{e,d,a}$ is the average daily consumed EE, on annual base. However, to use all the maximum storable energy, the battery size has to be designed considering that the DOD has to be lower than 100%, using the following equation:

$$S_b = \frac{E_{ss,max}}{DOD} * 100 \tag{18}$$

Where S_b represents the battery size. The choice to use the data on annual base is given by the oversizing or under-sizing problem of the storage system. Indeed, taking into account a battery with a larger size, this would have a better performance in the summer period, when there is a higher amount of EE to store by the PV production, while it would result oversized in the winter, when the PV production is lower. The opposite case occurs by considering a battery with a smaller size, that corresponds with the under-sizing phenomenon.

As concern the hydrogen storage, to properly compare the two technologies the electrolyser has been designed according to the battery size, at same input conditions. This means that the number of modules of electrolyser have been chosen in order that they can consume an amount of EE equal to that used by the battery, considering the DOD also. The energy consumed by each module is calculated as the product of the operative power consumption, equal to 2,4 kW, and the operational time, that depends on the PSH. Therefore, the number of electrolyser modules (N_e) to be applied is expressed by the following Equation:

$$N_e = \frac{S_b}{P_{EC,e} * PSH} \tag{19}$$

In this way, the hydrogen storage system results oversized with respect the battery, thus, it is also able to exploit the increasing amount of PV energy production during the summer, that coincides with a higher hydrogen production. Then, if the end user energy consumption remains unchanged, this could generate a supply of hydrogen for the winter, since the metal hydrides tank does not suffer of self-discharge. However, this is not appreciable with the analysis on the annual basis but has been studied in detail in the subsequent monthly analysis [Chapter 6].

Once the size of the storage system has been designed, to consider the out-coming energy ($E_{ss,out}$) it is needed to take into account the corresponding efficiencies of the different applied technologies (η_{ss}) by using the following equation:

$$E_{ss,out} = E_{ss,max} * \eta_{ss} \tag{20}$$

As concern the possible scenarios that can occur during the night:

- $E_{e,n} - E_{ss,out} < 0 = E_{ss,r}$, in this case the EE consumed during the night by the end users is totally covered by the storage system. Further, because of the energy contained into the storage system is higher than that required by the users, a reserve of energy ($E_{ss,r}$) to use in the following days is generated. This means that also after the discharging of the storage system $SOC > SOC_{min}$. This situation is represented in the Figure 5.8.

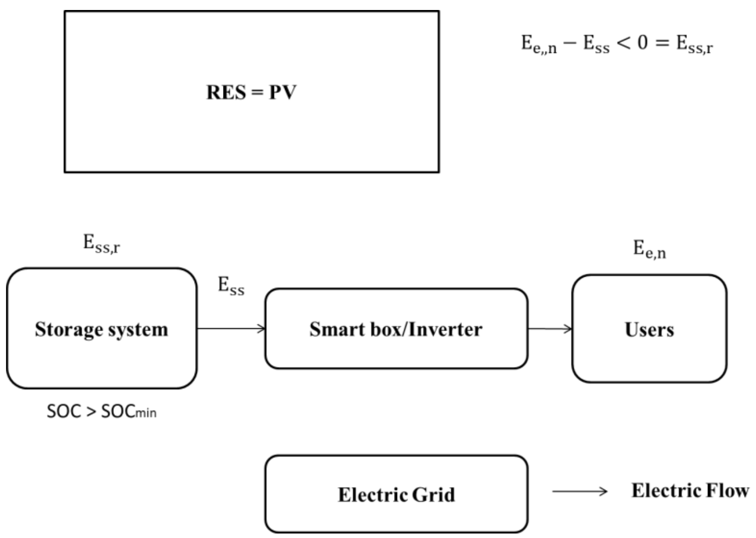

Figure 5.8. EE consumed during the night totally covered from the storage system with the possibility to generate a reserve of energy for the following days.

- $E_{e,n} - E_{ss} = 0$, in this case, the EE contained into the storage system is totally used to cover the energy required during the night, until the $SOC = SOC_{min}$. Therefore, there is not the possibility to reserve energy into the storage system for the following days.

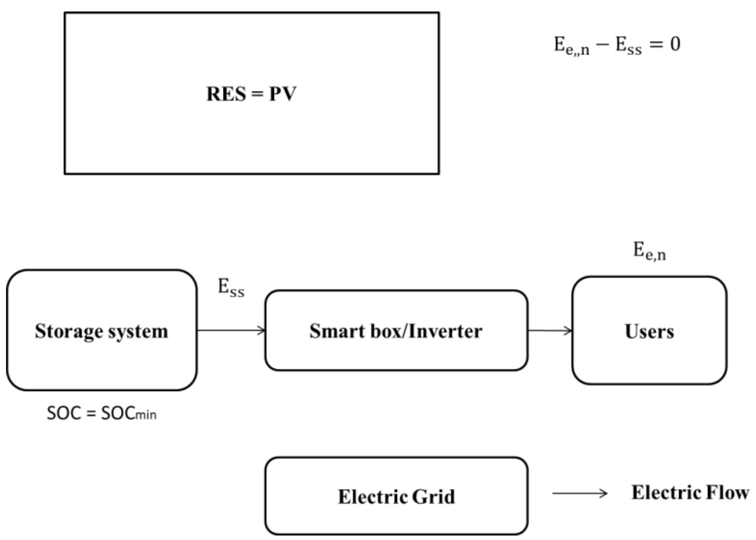

Figure 5.9. EE consumed during the night totally covered by the storage system.

- $E_{e,n} - E_{ss,out} > 0 = E_{d,n}$, in this case all the EE contained into the storage system is discharged until the $SOC = SOC_{min}$. However, this is not sufficient to satisfy the demand, therefore, the

$E_{d,n}$ represents the energy deficit during the night, that has to be imported from the grid, as represented in the Figure 5.10.

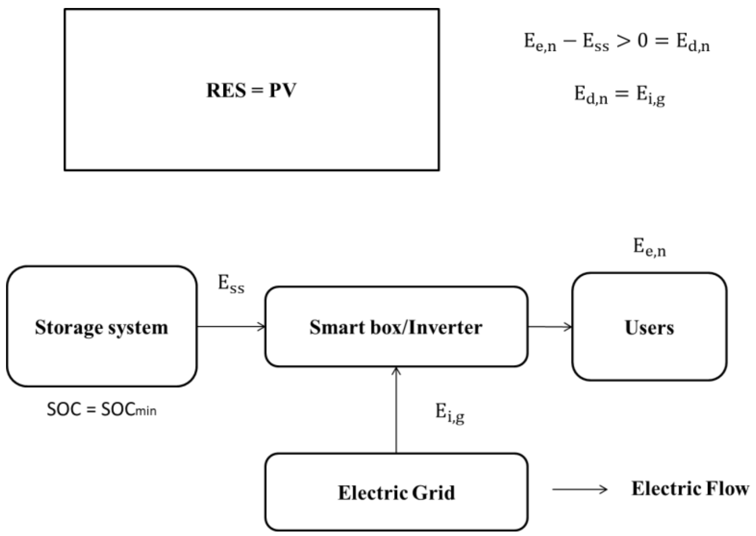

Figure 5.10. EE consumed during the night supplied both from the storage system and the grid.

Instead, as said in the introduction of the chapter, the SWH system is able to cover a given percentage of the E required by the users, depending on the location. The remaining part is covered by the auxiliary boiler (E_{a-b}). However, the amount of energy that has to be provided by the external heater is reduced in the case of the SWH system is matched with the hydrogen-based system. This is because a certain amount of TE is recovered by the waste heat of the electrolyser and fuel cell.

Once the method to carry out the energy balance and the design of the storage systems on annual base have been described, also the main performance parameters of the plant have been defined:

- The EE supplied to the users (E_{s-u}) is the self-consumed energy net of losses [10]. Therefore, it is equal to the sum of the EE by the PV and directly consumed during the day plus EE stored and released during the night or in the following days, considering the corresponding storage system efficiency, and calculated by using the following equation:

$$E_{s-u} = E_{e,d,a} + E_{ss,out} \tag{21}$$

- The electrical self-sufficiency (SS) measures the amount of the EE consumption supplied by the local generation with respect to the total consumption [10]. Therefore, it is equal to the ratio between the EE supplied and the EE required by the end users, it is expressed by the following equation:

$$SS = \frac{E_{s-u}}{E_e} \tag{22}$$

If this parameter is lower than 1, it means that a given amount of EE has to be imported from the grid, therefore the system is not totally independent. While, in the opposite case, the plant is totally independent and could satisfy the average EE demand by itself. Further, it could be possible to create an energy supply for the following day and/or export its to the grid.

- The EE exchanged with the grid (E_g) represents the balance of the imported and exported electricity through the grid. If this parameter has a negative value, it means that on average the amount of energy corresponding to this value has to be imported from the grid, otherwise this is exported to the grid. However, considering the analysis based on annual data, this only depends on the value of self-sufficiency.

While, considering both the EE and TE balance, the following parameters have been considered:

- The overall (EE and TE) self-sufficiency (SS_{oa}) represents the percentage of both required EE and TE by the users that the PV plant and the SWH plant with the corresponding storage systems are able to satisfy. Therefore, it is equal to the ratio between the sum of EE supplied to the users, the TE generated from the SWH system and eventually the heat recovered from the cogeneration system and overall energy required by the end users, as expressed by the following equation:

$$SS_{oa} = \frac{E_{s-u} + E_{SWH} + E_c}{E_e + E_{th}} \tag{23}$$

Where E_c represents the TE recovered by the cogeneration system. In the case of the battery $E_c = 0$.

- The overall (EE and TE) efficiency (η_{oa}) is defined as the ratio of the energy output and the energy input [53], considering the different systems, as represented in the Figure 5.11. and Figure 5.12. The first term is the sum of the EE supplied to the users, the TE covered from the SWH system, the TE recovered from the cogeneration system and the exported EE to the grid. Instead, the second term is the sum of the total EE supplied from the PV plant, the TE covered from the SWH system, the TE supplied by the boiler system and the imported EE by the grid. Thus, this is calculated by using the following equation:

$$\eta_{oa} = \frac{E_{s-u} + E_{SWH} + E_c + E_{e,g}}{E_{PV,e} + E_{SWH} + E_{a-b} + E_{i,g}} \tag{24}$$

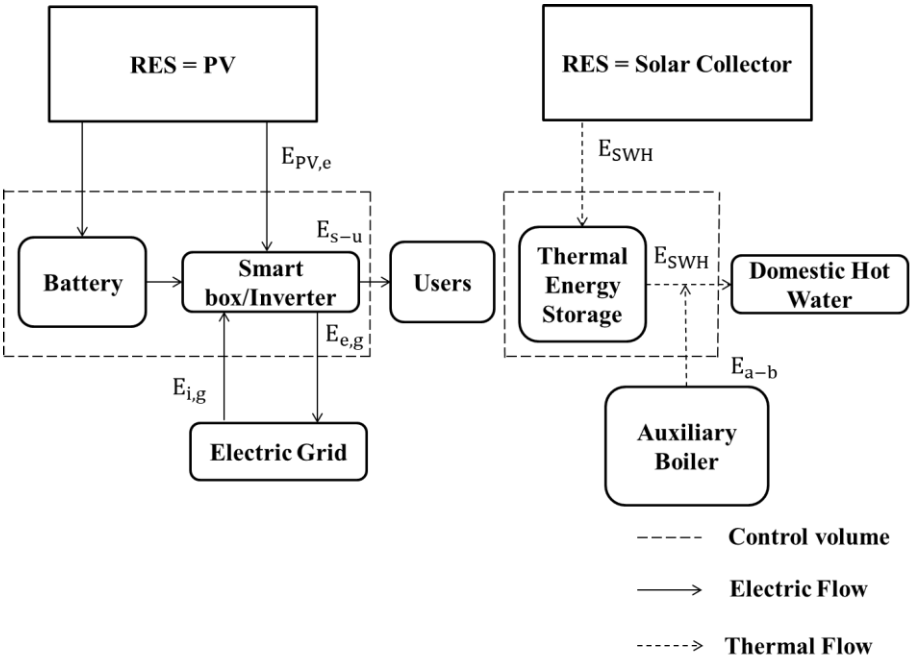

Figure 5.11. EE and TE input and output in the case of battery as storage system.

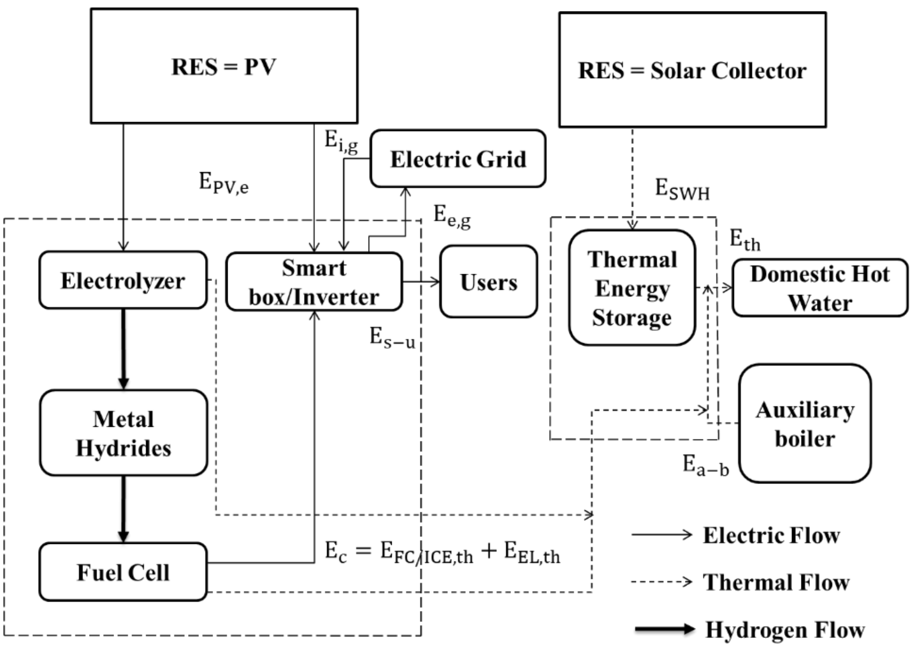

Figure 5.12. EE and TE input and output in the case of hydrogen storage system.

5.2. Analysis of 20 kW$_p$ PV plant with storage system: Milan

Considering Milan as the starting point of the analysis, and as representative of North Italy region, the corresponding energy performances of the plants can be taken from the Table 5.1. (Page 50). Therefore, as concern the EE production, considering 20 kW$_p$ of PV power, the average daily generated EE is equal to 68,49 kWh_e/d. Further, the average daily consumed EE by the end users can be calculated from the value (reported in the introduction) of the average annual energy consumption for a single Italian family. This value is equal to 71,73 kWh_e/d, of which 23,91 kWh_e/d is consumed during the day, while the remaining part, corresponding to 47,82 kWh_e/d, is consumed during the night. Thus, on average the daily consumed EE during the light hours is totally covered by the PV plant. In the same way, the average daily consumed TE by the end users for the DHW can be calculated. This value is equal to 164,38 kWh_{th}/d, of which 82,19 kWh_{th}/d are generated by the SWH system.

Moreover, as concern the storage system, the design of the battery is carried out in such a way that it is able to store all the average exceeding amount of EE during the day ($E_{ss,max}$), corresponding to the value 44,58 kWh_e/d, considering the Equation (17) (Page 54). Further, the DOD has to be taken into account as a battery design parameter and it is considered equal to 70%. Therefore, the size of the battery (S_b) is calculated by using the Equation (18), (Page 54), and it results equal to 63,68 kWh_e.

However, the out-coming EE ($E_{ss,out}$) by the battery is evaluated considering its electrical round-trip efficiency, corresponding to 90%, as shown in the Equation (20), (Page 55) resulting equals to 40,12 kWh_e/d.

This means that, on average, the EE that PV plant with the battery is able to store and release is lower than the daily consumed energy during the night by the end users ($E_{e,n,a}$). Therefore, a given amount of EE, corresponding to 7,70 kWh_e/d, is needed to be imported from the grid ($E_{i,g}$) to fully meet the demand. Consequently,

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 64,03 kWh_e/d, by applying the Equation (21) (Page 57).
- The electrical self-sufficiency (SS) of the system results to be equals to 89,27%, by applying the Equation (22) (Page 57).
- The EE exchanged with the grid (E_g) is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE balance, it is known that the installed SWH system is able to cover the 50% of the average daily required TE, corresponding to 82,19 kWh_{th}/d. The remaining part is covered by the auxiliary boiler. Thus, for the overall performance parameters result that:

- The overall self-sufficiency (SS_{oa}) is equal to about 61,93%, calculated through the Equation (23) (Page 58).
- The overall efficiency (η_{oa}) is equal to about 60,78%, applying the Equation (24) (Page 58).

While as concern the hydrogen storage, the size is defined as the electrolyser nominal power consumption ($P_{EC,e}$), that represents the amount of power that is needed to obtain a certain amount of hydrogen. As said previously, the electrolyser size is defined in order that the modules of electrolyser are able to consume an amount of EE equal to the battery size, in this case 63,68 kWh_e. Therefore, the number of modules that have to be applied to satisfy the design characteristic is equal to 6, applying the Equation (19) (Page 55), corresponding to a total nominal electrical power consumption of 14,4 kW_e. Further, considering that during the operational time, each module of electrolyser is able to produce 0,21 kg_{H2}/d of hydrogen, with an EE consumption of 11,12 kWh_e/d, if the PV plant is able to satisfy the required EE supply, the electrolyser section would be able to produce 1,25 kg_{H2}/d. This corresponds to 41,66 kWh_{ch}/d of chemical energy stored into metal hydrides tank through the hydrogen, considering its energy content of 33,33 kWh_{ch}/ kg_{H2}.

However, in this case the average EE available to the functioning of the electrolyser is equal to 44,58 kWh_e/d. Therefore, they are able to produce only 0,83 kg_{H2}/d of hydrogen and a corresponding chemical energy of 27,82 kWh_{ch}/d is stored. Then, considering that the fuel cell efficiency is equal to 50%, the out-coming energy ($E_{ss,out}$) is equal to 13,91 kWh_e/d.

Also in this case, on average, the EE that PV plant with the hydrogen storage system is able to store and release is lower than the daily consumed energy during the night by the end users ($E_{e,n,a}$). Therefore, an amount of energy, corresponding to 33,91 kWh_e, must be imported from the grid ($E_{i,g}$) to fully meet the demand.

Once the EE balance from the electrical point of view have been carried out, the main parameters are possible to be calculated:

- The EE supplied to the users (E_{s-u}) results to be equal to 37,82 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 55,73%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE balance, the value of the average daily required TE covered from the SWH system is always the same, corresponding to 82,19 kWh_{th}. However, in this case, the TE recovered from both the electrolyser and the fuel cell during their functioning has to be considered. Indeed, the first one produces a heat flow equal to around the 20% of the consumed EE for the hydrogen production, corresponding to 13,91 kWh_{th}/d. While second one produces a heat flow equal to around the 50% of the consumed chemical energy for the EE production, corresponding to 13,91 kWh_{th}/d. The remaining part of the required TE is covered by the auxiliary boiler, that is equal to 59,18 kWh. Consequently,

- The overall self-sufficiency (SS_{oa}) is equal to around 60,57%.
- The overall efficiency (η_{oa}) is equal to around 58,67%.

The-same considerations can be done in the case of the hydrogen storage system with ICE. This although it presents a change in the EE and TE balance, due to the different efficiencies of the engine. Indeed, it presents an electrical efficiency equal to 26% and a thermal one equal to 62%.

Therefore, always considering the average daily production of 0,83 kg_{H2}/d of hydrogen from the electrolyser, that corresponds to 27,82 kWh_{ch}/d of chemical energy, the produced EE by the ICE is equal to 7,23 kWh_e/d. Also in this case, the energy that has to be imported from the grid to meet the demand during the night is equal to 40,58 kWh_e/d. Concluding,

- The EE supplied to the users (E_{s-u}) is equal to 31,14 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 43,42%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE balance, the ICE presents a high thermal efficiency that allows to recovery an amount of heat, equal to 17,25 kWh_{th}/d. The electrolyser always produces the same amount of TE. Therefore, the average TE needed from the auxiliary boiler is equal to 55,84 kWh_{th}/d. Thus,

- The overall self-sufficiency (SS_{oa}) is equal to around 59,16%.
- The overall efficiency (η_{oa}) is equal to around 56,53%.

5.2.1. Analysis of 30 kW_p PV plant with storage system: Milan

Increasing to 30 kW_p the value of the PV power, the average daily PV production is equal to 102,73 kWh_e/d. Again, the average daily consumed EE during the light hours is totally covered by the PV.

In this case, the average exceeding amount of EE during the day ($E_{ss,max}$), is equal to 78,82 kWh_e/d, considering the Equation (17). Therefore, the size of the battery (S_b) results equal to 112,60 kWh_e, calculated by using the Equation (38).

The out-coming EE ($E_{ss,out}$) from the battery is evaluated considering its electrical round-trip efficiency, corresponding to 90%, as shown in the Equation (20), resulting equals to 70,94 kWh_e/d.

This means that, in this case, the EE that PV plant with the battery is able to store and release is higher than the daily consumed EE during the night by the end users ($E_{e,n,a}$). Therefore, a given amount of energy, corresponding to 23,12 kWh_e/d, can be used as a reserve to the following days and/or exported to the grid ($E_{e,g}$).

Following the same procedure previously exposed, it is obtained that:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 94,85 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 132,23%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy exported to the grid ($E_{e,g}$).

As concern the TE balance, it remains unchanged with respect to the previous case, and it is obtained that:

- The overall self-sufficiency (SS_{oa}) is equal to around 74,98%.
- The overall efficiency (η_{oa}) is equal to around 66,28%.

While as concern the hydrogen storage, the design of the electrolyser size is made in order that the modules are able to consume the same amount of energy of the battery size, equal to 112,60 kWh_e. Therefore, in this case the number of modules that have to be applied to satisfy the design characteristic is equal to 10, corresponding to a total nominal electrical power consumption of 24 kW_e. Further, considering that during the operational time, each module of electrolyser is able to produce 0,21 kg_{H2}/d of hydrogen, with an energy consumption of 11,12 kWh_{ch}/d. Therefore, if the PV plant is able to satisfy the required energy from all the modules of electrolyser, they would be able to produce 2,1 kg_{H2}/d. This corresponds to 69,4 kWh_{ch}/d of chemical energy stored into metal hydrides tank through the hydrogen,

However, in this case the average EE available to the functioning of the modules of electrolyser is equal to 78,82 kWh_e/d. Therefore, they are able to produce only 1,48 kg_{H2}/d of hydrogen and a corresponding chemical energy of 49,19 kWh_{ch}/d. Then, considering that the fuel cell efficiency is equal to 50%, the outcoming EE ($E_{ss,out}$) is equal to 24,60 kWh_e/d

Also in this case, on average, the EE that PV plant with the hydrogen storage system is able to store and release is lower than the daily consumed energy during the night by the end users ($E_{e,n,a}$). Therefore, a given amount of EE, corresponding to 23,22 kWh_e/d, is needed to be imported from the grid ($E_{i,g}$) to fully meet the demand. For the 30kW_p PV is obtained that:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 48,50 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 67,62%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE balance, the value of the average daily required TE covered with the SWH system is always the same, corresponding to 82,19 kW_{th}/d. However, in this case, the thermal energy recovered from both the electrolyser and the fuel cell during their functioning has to be considered. Indeed, the first one produces a heat flow equal to around the 20% of the energy consumed for the hydrogen production, corresponding to 16,09 kWh_{th}/d. While second one produces a heat flow equal to around the 50% of the chemical energy consumed for the energy production, corresponding to 24,60 kWh_{th}/d. The remaining part is covered by the auxiliary boiler, that is equal to 41,50 kWhth/d. Consequently,

- The overall self-sufficiency (SS_{oa}) is equal to around 72,59%.
- The overall efficiency (η_{oa}) is equal to around 68,65%.

As said in the previous paragraph, the hydrogen storage system with ICE presents only a change in the EE and TE balance, due to the different efficiencies of the engine. Indeed, it presents an electrical efficiency equal to 26% and a thermal one equal to 62%.

Therefore, always considering the average daily production of 1,48 kg_{H2}/d of hydrogen from the electrolyser, that corresponds to 49,19 kWh_{ch}/d of chemical energy, used as a fuel for engine, the produced EE from the ICE is equal to 12,79 kWh_e/d. Also in this case, the energy that has to be imported from the grid to meet the demand during the night is equal to 35,03 kWh_e/d. Thus,

- The EE supplied to the users (E_{s-u}) is equal to 36,70 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 51,16 %.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE balance, the ICE presents a high thermal efficiency that allows to recovery an amount of heat equal to 30,50 kWh_{th}/d. While the electrolyser always produces the same amount of TE. The TE needed to fully meet the demand is reduced to 35,60 kWh_{th}/d. Then we obtain that

- The overall self-sufficiency (SS_{oa}) is equal to around 70,09%.
- The overall efficiency (η_{oa}) is equal to around 64,76%.

5.2.2. Analysis of 40 kW_p PV plant with storage system: Milan

Considering 40 kW_p of the PV power, the average daily PV production is equal to 136,97 kWh_e/d, and the average daily consumed electrical energy during light hours is totally covered by the PV plant.

In this case, the average exceeding amount of EE during the day ($E_{ss,max}$), is equal to 113,06 kWh_e/d, therefore, the size of the battery (S_b) results equal to 161,52 kWh_e.

The outcoming EE ($E_{ss,out}$) from the battery is evaluated considering its electrical round-trip efficiency, corresponding to 90%, resulting equals to 101,76 kWh_e/d.

This means that, also in this case, the EE that PV plant with the battery is able to store and release is higher than the daily consumed energy during the night by the end users ($E_{e,n,a}$). Therefore, a given amount of EE, corresponding to 53,94 kWh_e/d, can be used as a reserve to the following days and/or exported to the grid ($E_{e,g}$).

The main electrical parameters for this case are:

- The EE supplied to the users (E_{s-u}) results to be equal to 125,66 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 175,20%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy exported to the grid ($E_{e,g}$).

About the TE balance, it remains unchanged with respect to the previous case. Thus,

- The overall self-sufficiency (SS_{oa}) is equal to around 88,03%.
- The overall efficiency (η_{oa}) is equal to around 68,97%.

Concerning the hydrogen storage, as the battery size is equal to 161,52 kWh_e/d, the number of electrolyser modules that have to be applied to satisfy the design characteristic is equal to 15, corresponding to a total nominal electrical power consumption of 36 kW_e. Further, considering that during the operational time, each module of electrolyser is able to produce 0,21 kg_{H2}/d of hydrogen, with an EE consumption of 11,12 kWh_e/d. Therefore, if the PV plant is able to satisfy the required energy from all the modules of electrolyser, they would be able to produce 3,15 kg_{H2}/d. This corresponds to 104,98 kWh_{ch}/d of chemical energy stored into metal hydrides tank through the hydrogen,

However, in this case the average electrical energy available to the functioning of the modules of electrolyser is just 113,06 kWh_e/d. Therefore, they are able to produce only 2,12 kg_{H2}/d of hydrogen and a corresponding chemical energy of 70,56 kWh_{ch}/d. Then, considering that the fuel cell efficiency is equal to 50%, the outcoming energy ($E_{ss,out}$) is equal to 35,28 kWh_e/d

Also in this case, on average, the EE that PV plant with the hydrogen storage system is able to store and release is lower than the daily consumed energy during the night by the end users ($E_{e,n,a}$). Therefore, a given amount of EE, corresponding to 12,54 kWh_e/d, is needed to be imported from the grid ($E_{i,g}$) to fully meet the demand. Consequently,

- The EE supplied to the users (E_{s-u}) results to be equal to 59,19 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 82,52%.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As in previous case, the thermal energy needs covered from by SWH system is always the same, corresponding to 82,19 kWh_{th}/d. However, considering the TE recovered from both the electrolyser and the fuel cell during their working time , 23,08 kWh_{th}/d from electrolyser and 35,28 kWh_{th}/d from FC, just the remaining part is covered by the auxiliary boiler, an average of 23,83 kWh/d. This results in:

- The overall self-sufficiency (SS_{oa}) is equal to around 84,60%.
- The overall efficiency (η_{oa}) is equal to around 78,17%.

As said in the previous paragraph, taking into account, the hydrogen storage system with ICE, it presents only a change in the EE and TE balance, due to the different efficiencies of the engine. Therefore, always considering the average daily production of 2,12 kg_{H2}/d of hydrogen from the electrolyser, that corresponds to 70,56 kWh_{ch}/d of chemical energy, used as a fuel for engine, the produced EE from the ICE is equal to 18,35 kWh_e/d, and the energy that has to be imported from the grid to meet the demand during the night is equal to 29,74 kWh_e/d. Thus,

- The EE supplied to the users (E_{s-u}) is equal to 42,25 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 58,91 %.
- The EE exchanged with the grid (E_g) in this case is only equal to the energy imported from the grid ($E_{i,g}$).

As concern the TE, the ICE allows to recovery 43,75 kWh_{th}/d, while the electrolyser always produces the same amount of TE. The thermal energy needed to fully meet the demand is reduced to 15,36 kWh_{th}/d. Thus,

- The overall self-sufficiency (SS_{oa}) is equal to 81,01%, about.
- The overall efficiency (η_{oa}) is equal to about 72,46%.

5.2.3. Graphical visualizations and comments of the obtained results: Milan

In the previous paragraphs, the results of the average electrical and thermal energy balances on annual base, of the design of the storage system and the performance parameters in the case of Milan at the different installed PV power have been obtained. These have been summarized in the Table 5.2. Moreover, the main performance parameters are represented in the Figure 5.13., Figure 5.14. and Figure 5.15. In this way, it is easier to make a comparison between the different applied storage systems at the different installed PV powers in Milan.

Table 5.2. Summary of the energy balance, storage system and performance of the plant.

	Milan									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Average energy requirements										
Average EE consumption	71,73			71,73			71,73			[kWh/d]
Average EE consumption during the day	23,91			23,91			23,91			[kWh/d]
Average EE consumption during the night	47,82			47,82			47,82			[kWh/d]
Average TE consumption	164,38			164,38			164,38			[kWh/d]
Renewable tecnologies										
Installed PV power	20	30	40	20	30	40	20	30	40	[kWp]
Collector area	40			40			40			[m^2]
Storage tank volume	2000			2000			2000			[l]
Average renewable energy										
Average produced EE from the PV	68,49	102,73	136,97	68,49	102,73	136,97	68,49	102,73	136,97	[kWh/d]
Average produced TE from the SWH	82,19			82,19			82,19			[kWh/d]
Design of the storage system										
Battery size	63,69	112,60	161,51	[-]			[-]			[kWh]
Maximum EE consumable by electrolyser	[-]			63,69	112,60	161,51	63,69	112,60	161,51	[kWh/d]
Electrolyser size	[-]			14,4	24	36	14,4	24	36	[kW]
Storage capability metal hydrides	[-]			9286,8	16421	23555	9286,8	16421	23555	[l/d]
Metal hydrides size (Geometrical volume)	[-]			750	750	750	750	750	750	[l]
FC/ICE size	[-]			1,55	2,73	3,92	0,8	1,42	2	[kW]
EE balance										
Storable EE during the day	44,58	78,82	113,06	44,58	78,82	113,06	44,58	78,82	113,06	[kWh/d]
Hydrogen production	[-]			0,83	1,48	2,12	0,83	1,48	2,12	[kg/d]
Energy stored via hydrogen	[-]			27,66	49,33	70,66	27,66	49,33	70,66	[kWh/d]
EE output	40,12	70,94	101,75	13,83	24,66	35,33	7,19	12,83	18,37	[kWh/d]
Imported/exported EE during the night	-7,70	23,12	53,93	-33,99	-23,16	-12,49	-40,63	-34,99	-29,45	[kWh/d]
EE supplied to the users	64,03	94,85	125,66	37,74	48,57	59,24	31,10	36,74	42,28	[kWh/d]
Elecrtrical self-sufficiency	**89,27**	**132,23**	**175,19**	**52,62**	**67,72**	**82,59**	**43,36**	**51,21**	**58,95**	[%]
TE balance										
Recovered TE via electrolyser	[-]			8,92	15,76	22,61	8,92	15,76	22,61	[kWh/d]
Recovered TE via FC/ICE	[-]			13,83	24,66	35,33	17,15	30,58	43,81	[kWh/d]
TE from the boiler system	82,19			59,44	41,76	24,25	56,12	35,84	15,77	[kWh/d]
Overall self-sufficiency	**61,93**	**74,98**	**88,03**	**60,57**	**72,59**	**84,6**	**59,16**	**70,09**	**81,01**	[%]
Overall efficiency	**60,78**	**66,28**	**68,97**	**58,67**	**68,65**	**78,17**	**56,53**	**64,76**	**72,46**	[%]

Looking at the Table 5.2. it is possible to see that a growing size of the storage system with the increase of the installed PV power was applied. This is needed to maximize the self-sufficiency of the system, because increasing the size of the PV plant, the average storable energy during the day increases, and if the size of storage system remains the same it would not be possible to accumulate the extra amount of the exceeding energy during the day. Instead, by increasing the size of the storage system, the energy that can be stored during the day increases, also increasing the energy supplied to the end users. Therefore, the electrical self-sufficiency linearly grows as a function of the installed PV power, as shown in the Figure 5.13.

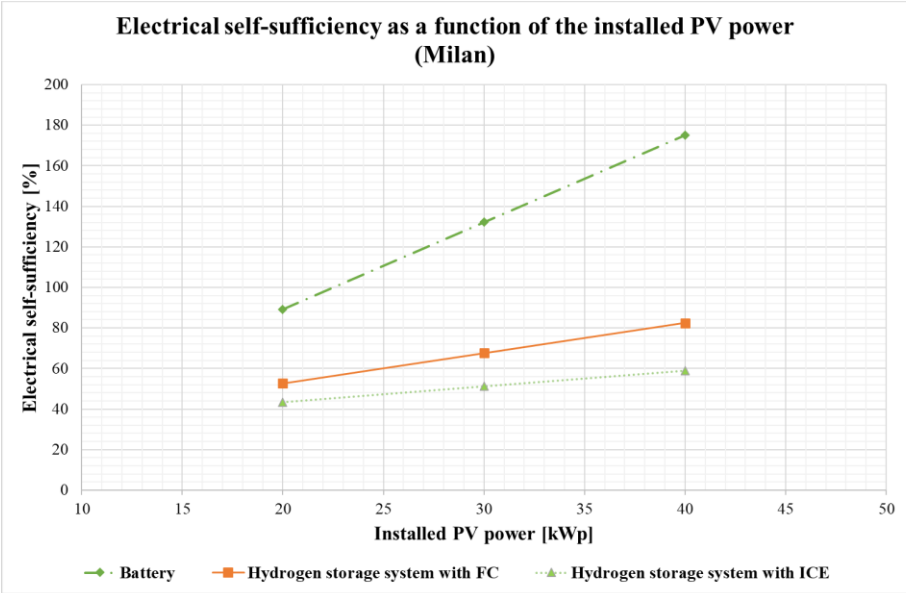

Figure 5.13. Electric self-sufficiency of the system located in Milan.

Further, it is possible to see that, the value of the electrical self-sufficiency of the system with the battery is always higher than in the case with the hydrogen storage system. Moreover, the first one presents a line of the self-sufficiency with a greater slope in respect to the second one. These differences are due to the higher electrical efficiency of the battery in respect to the electrolyser and FC/ICE, that allows to a lower loss of electrical energy during the storage and releasing, resulting in a more quick increase of the energy supplied to the users and of the self-sufficiency.

Moreover, the electric self-sufficiency of the 20 kW_p PV system is in any case lower than 100%. This means that the systems need to be supported from the grid to fully meet the end users' demand. However, the plant with battery as storage system presents an electric self-sufficiency over 100% for an installed PV of 30 kW_p, becoming independent from the grid. Going over 100% of the self-sufficiency means that the system is able to store electrical energy also for the following days or to exports it to the grid. Instead, the plant with the hydrogen storage system presents a self-sufficiency lower than 100% also at an installed PV power equal to 40 kW_p, thus it always dependent from the electric grid.

Although for the residential application the issue it is not just the electric energy, but the whole energy supply, i.e. electric and thermal, it is important to note that by this annual average analysis, with the imposed constriction, we can conclude that the hydrogen storage is not convenient for the electric energy self-sufficiency.

Results considering both electric and thermal energy are shown in Figure 5.4 that return a clearly competitive situation.

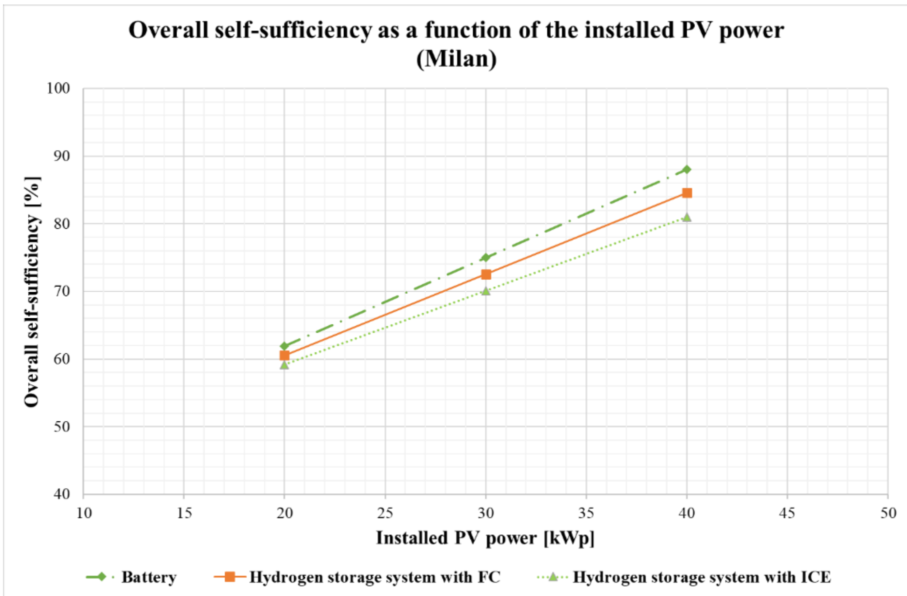

Figure 5.14. Overall self-sufficiency for the systems located in Milan.

The results are close each other and the slope of the lines is almost the same. This difference with respect the previous case is due to the recovery of thermal energy obtained in the case of hydrogen storage approach. Indeed, also this recover linearly grows as a function of the installed PV power and compensates for the greater amount of electrical energy lost due to the lower electrical efficiency.

While as concern the overall efficiency, it presents a non-linear trend in the case of the plant with battery, as shown in the Figure 5.15.

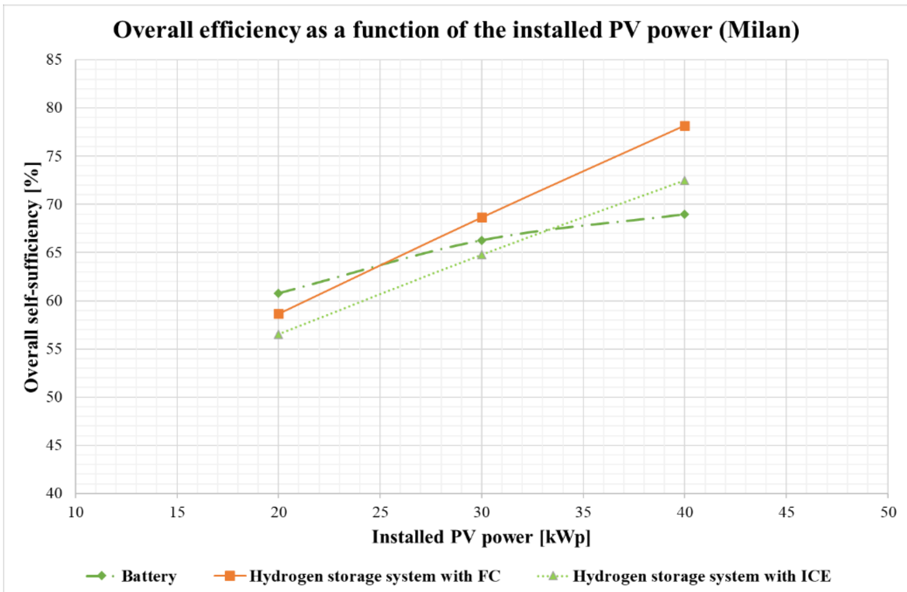

Figure 5.15. Overall efficiency of the system located in Milan.

Moreover, despite the overall efficiency in the case of battery presents a higher value at 20 kW_p of PV power than those of the hydrogen storage system, it seems to become lower at the increasing of the PV power. Indeed, this already occurs at 30 kW_p PV in the case of hydrogen storage system with FC, and just at 40 kW_p PV the case of ICE.

5.3. Analysis of the PV plant with storage system: Rome

Once the only variable to take into account are the PV specific annual energy production and the percentage of covered thermal energy by the SWH system, moving from a location to another one, exactly the same procedure of the previous paragraphs is applied in the case of Rome, representing the Centre Italy region.

In analogy with Milan case, the results are summarised in the Table 5.3. Moreover, the main performance parameters are plotted in the Figure 5.17., Figure 5.18. and Figure 5.19. In this way, it is easier to make a comparison between the different applied storage systems at the different installed PV powers in Rome, also making a comparison with the case of Milan (Table 5.2).

Table 5.3. Summary of the energy balance, storage system and performance of the plant.

	Rome									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Average energy requirements										
Average EE consumption	71,73			71,73			71,73			[kWh/d]
Average EE consumption during the day	23,91			23,91			23,91			[kWh/d]
Average EE consumption during the night	47,82			47,82			47,82			[kWh/d]
Average TE consumption	164,38			164,38			164,38			[kWh/d]
Renewable tecnologies										
Installed PV power	20	30	40	20	30	40	20	30	40	[kWp]
Collector area	40			40			40			[m^2]
Storage tank volume	2000			2000			2000			[l]
Average renewable energy										
Average produced EE from the PV	79,49	119,23	158,98	79,49	119,23	158,98	79,49	119,23	158,98	[kWh/d]
Average produced TE from the SWH	90,41			90,41			90,41			[kWh/d]
Design of the storage system										
Battery size	79,40	136,17	192,96	[-]			[-]			[kWh]
Maximum EE consumable by electrolyser	[-]			76,15	139,62	190,39	76,15	139,62	190,39	[kWh/d]
Electrolyser size	[-]			14,4	26,4	36	14,4	26,4	36	[kW]
Storage capability metal hydrides	[-]			11579	19859	28139	9286,8	19859	28139	[l/d]
Metal hydrides size (Geometrical volume)	[-]			33,4	50,1	66,8	33,4	50,1	66,8	[l]
FC/ICE size	[-]			1,93	3,3	4,68	1	1,72	2,44	[kW]
EE balance										
Storable EE during the day	55,58	95,32	135,07	55,58	95,32	135,07	55,58	95,32	135,07	[kWh/d]
Hydrogen production	[-]			1,04	1,79	2,53	1,04	1,79	2,53	[kg/d]
Energy stored via hydrogen	[-]			34,70	59,49	84,32	34,70	59,49	84,32	[kWh/d]
EE output	50,02	85,79	121,56	17,35	29,75	42,16	9,02	15,47	21,92	[kWh/d]
Imported/exported EE during the night	2,20	37,97	73,74	-30,47	-18,07	-5,66	-38,80	-32,35	-25,90	[kWh/d]
EE supplied to the users	73,93	109,70	145,47	41,26	53,66	66,07	32,93	39,38	45,83	[kWh/d]
Electrical self-sufficiency	**103,07**	**152,93**	**202,81**	**57,52**	**74,80**	**92,11**	**45,91**	**54,90**	**63,90**	[%]
TE balance										
Recovered TE via electrolyser	[-]			11,12	19,46	27,58	11,12	19,46	27,01	[kWh/d]
Recovered TE via FC/ICE	[-]			17,35	29,75	42,16	21,51	36,89	52,28	[kWh/d]
TE from the auxiliary boiler	73,97			45,51	24,77	4,23	41,34	17,38	0,00	[kWh/d]
Overall self-sufficiency	**69,6**	**84,75**	**99,9**	**67,92**	**81,86**	**95,8**	**66,15**	**78,94**	**91,66**	[%]
Overall efficiency	**67,93**	**70,56**	**72,95**	**65,28**	**76,55**	**87,23**	**62,52**	**71,86**	**78,62**	[%]

First, all the considerations that have been made in the case of Milan as concern the growth of the size of the storage system and the trend of the self-sufficiency at the different considered storage technologies with the increasing of the installed PV power are the same that in the case of Rome, as it is possible to see respectively from the Table 5.3. and Figure 5.17.

In Rome the size of the storage systems is higher than in Milan. This is due to the higher average produced PV production of electrical energy, that allows to have a higher amount of storable energy during the day. Therefore, the self-sufficiency in the case of Rome results to be slightly higher than that of Milan. Indeed, if the size of storage system in the case of Rome remained the same than in the case of Milan, it would not be possible to accumulate the extra amount of the storable energy during the day. Therefore, in this way the energy supplied to the end users and consequently the self-sufficiency would remain unchanged in the two cases. While, by increasing the size of the storage system, the energy that can be stored during the day increases, also increasing the energy supplied to the end users.

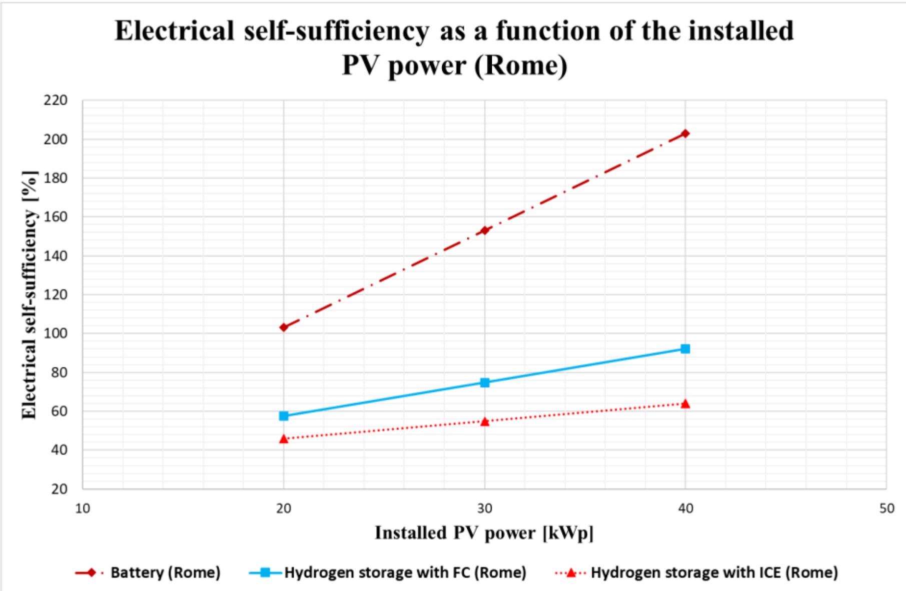

Figure 5.17. Electrical self-sufficiency of the system located in Rome.

Moreover, in respect to the case of Milan, the electric self-sufficiency of the PV system with the battery storage located in Rome is higher than 100% also at 20 kW_p of installed power, and, on average, the system does not need to be supported from the grid to fully meet the demand by the end user. Moreover, a further increasing of the self-sufficiency means that the system is able to store electrical energy also for the following days or to exports it to the grid. Instead, also in the case of Rome, the PV plant with the hydrogen storage system presents an electric self-sufficiency lower than 100% also at an installed PV power equal to 40 kW_p, thus it always dependent from the grid.

Also concerning the overall parameters, the consideration that have been made in the case of the plant located in Milan are almost the same of those of Rome, as it is shown in the Figure 5.18. and Figure 5.19.

First, both the overall self-sufficiency and the overall efficiency of the plant located in Rome presents slightly higher values than those of the plant located in Milan, for each installed PV power. This is mainly due to the higher percentage of covered thermal energy by the SWH located in Rome. Further, in the case of the hydrogen storage system, a higher value of electrical storable energy during the day means a higher hydrogen production by the electrolyser and consequently a higher value of recovered thermal energy from this. Moreover, a higher production of hydrogen also means that both the FC and the ICE can produce a higher value of output energy, both from the electrical and thermal point of view.

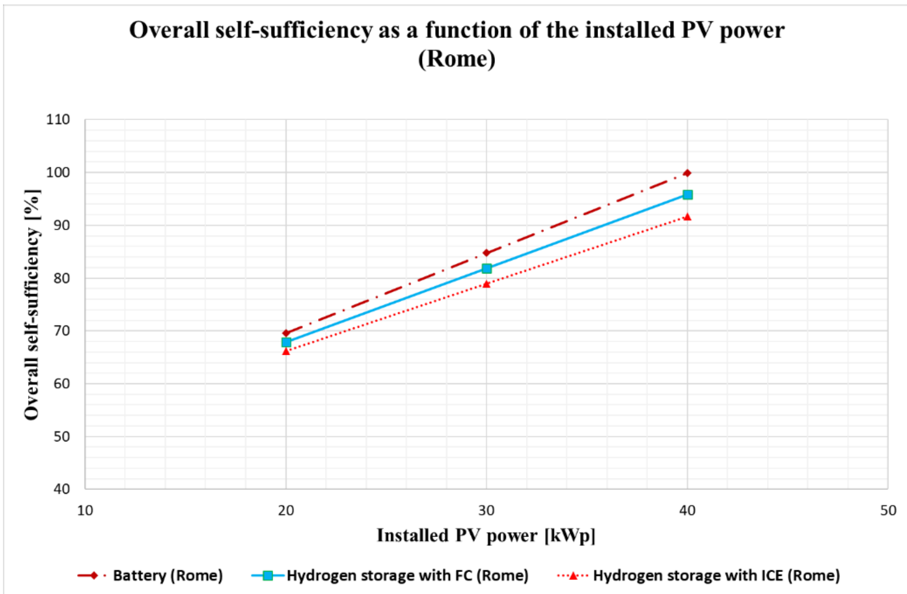

Figure 5.18. Overall self-sufficiency of the system located in Rome.

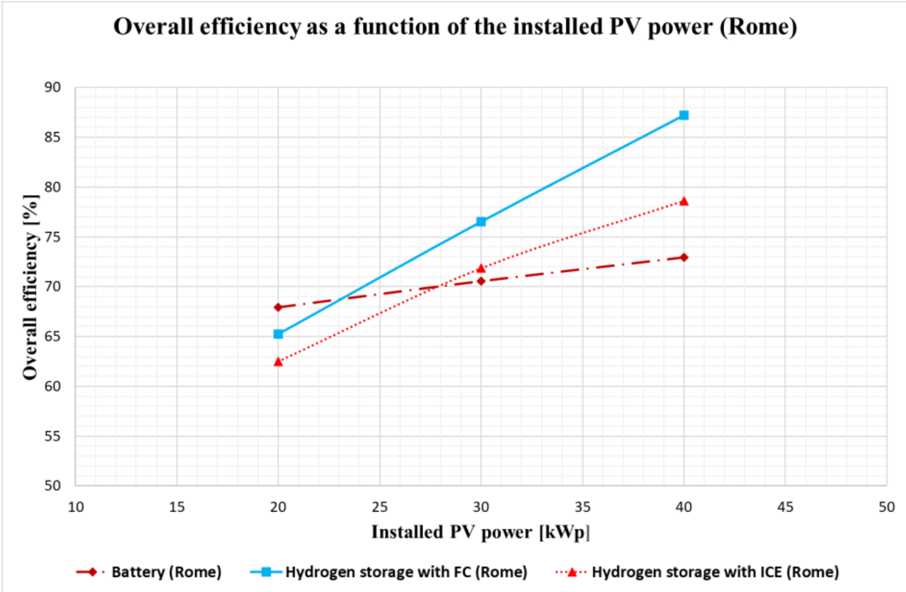

Figure 5.19. Overall efficiency of the system located in Rome.

However, this increasing of recovered thermal energy can generate a gain until a certain point. As a difference with the case of Milan, also the overall efficiency of the plant with the hydrogen storage system with ICE presents a non-linear trend. This is due to the exceeding amount of recovered thermal energy by the hydrogen storage system with respect the required one by the end users, that cannot be used to the DHW. Therefore, this generates a loss of thermal energy that grows with the increasing of the installed PV power that imply a penalty to the overall efficiency. In this case, this only occurs at 40 kW_p of the installed PV power.

Moreover, the overall efficiency in the case of plant with battery located in Rome presents a lower slope of the line with respect to the case of the same plant located in Milan. This means that the value of the overall efficiency in the case of the plant with battery located in Rome becomes quickly lower than the case of the plant with the hydrogen storage system always located in Rome, compared with the case of this plants located in Milan. Indeed, this seems to occur at around 25 kW_p in the case of hydrogen storage system with FC while around 30 kW_p in the case of ICE, against to respectively 25 kW_p and 35 kW_p of the same plants located in Milan.

5.4. Analysis of the PV plant with storage system: Syracuse

The calculations have been made for the city of Syracuse, representing the South of Italy area. Like for previous locations, results are summarized in the Table 5.4 and, the main performance parameters are represented in the Figure 5.21., Figure 5.22. and Figure 5.23, and a comparison with the case of Milan and Rome is done.

Table 5.4. Summary of the energy balance, storage system and performance of the plant.

	Syracuse									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Average energy requirements										
Average EE consumption	71,73			71,73			71,73			[kWh/d]
Average EE consumption during the day	23,91			23,91			23,91			[kWh/d]
Average EE consumption during the night	47,82			47,82			47,82			[kWh/d]
Average TE consumption	164,38			164,38			164,38			[kWh/d]
Renewable tecnologies										
Installed PV power	20	30	40	20	30	40	20	30	40	[kWp]
Collector area	40			40			40			[m^2]
Storage tank volume	2000			2000			2000			[l]
Average renewable energy										
Average produced EE from the PV	85,54	128,32	171,09	85,54	128,32	171,09	85,54	128,32	171,09	[kWh/d]
Average produced TE from the SWH	98,63			98,63			98,63			[kWh/d]
Design of the storage system										
Battery size	88,04	149,16	210,26	[-]			[-]			[kWh]
Maximum EE consumable by electrolyser	[-]			80,63	149,16	210,26	88,04	149,16	210,26	[kWh/d]
Electrolyser size	[-]			14,4	26,4	38,4	14,4	26,4	38,4	[kW]
Storahe capability metal hydrides	[-]			12841	16421	23555	9286,8	16421	23555	[l/d]
Metal hydrides size (Geometrical volume)	[-]			750	750	750	750	750	750	[l]
FC/ICE size	[-]			2,13	3,95	5,1	1,1	1,5	2,7	[kW]
EE balance										
Storable EE during the day	61,63	104,41	147,18	61,63	104,41	147,18	61,63	104,41	147,18	[kWh/d]
Hydrogen production	[-]			1,15	1,96	2,76	1,15	1,96	2,76	[kg/d]
Energy stored via hydrogen	[-]			38,33	65,16	91,85	38,33	65,16	91,85	[kWh/d]
EE output	55,47	93,97	132,46	19,16	32,58	45,93	9,97	16,94	23,88	[kWh/d]
Imported/exported EE during the night	7,65	46,15	84,64	-28,58	-15,24	-1,89	-37,85	-30,88	-23,94	[kWh/d]
EE supplied to the users	79,38	117,88	156,37	43,14	56,49	69,84	33,88	40,85	47,79	[kWh/d]
Electrical self-sufficiency	**110,66**	**164,34**	**218,00**	**60,14**	**78,75**	**97,36**	**47,23**	**56,95**	**66,63**	[%]
TE balance										
Recovered TE via electrolyser	[-]			12,58	21,32	30,05	12,33	21,32	30,05	[kWh/d]
Recovered TE via FC/ICE	[-]			19,23	32,58	45,93	24,01	40,40	56,95	[kWh/d]
TE from the auxiliary boiler	98,63			33,94	11,85	0,00	29,41	3,77	0,00	[kWh/d]
Overall self-sufficiency	**75,39**	**91,7**	**108**	**73,52**	**88,52**	**103,53**	**71,63**	**85,33**	**98,86**	[%]
Overall efficiency	**71,22**	**73,97**	**76,01**	**70,37**	**82,28**	**90**	**67,34**	**77,01**	**79,49**	[%]

Again, due to the higher average produced electrical energy from the PV, that allows to have a higher amount of storable energy during the day, a further increase of the storage size is present in respect to the case of Rome or Milam. Therefore, the self-sufficiency in the case of Syracuse results to be higher than that of Rome and Milan, as shown in the Table 5.4. and Figure 5.21.

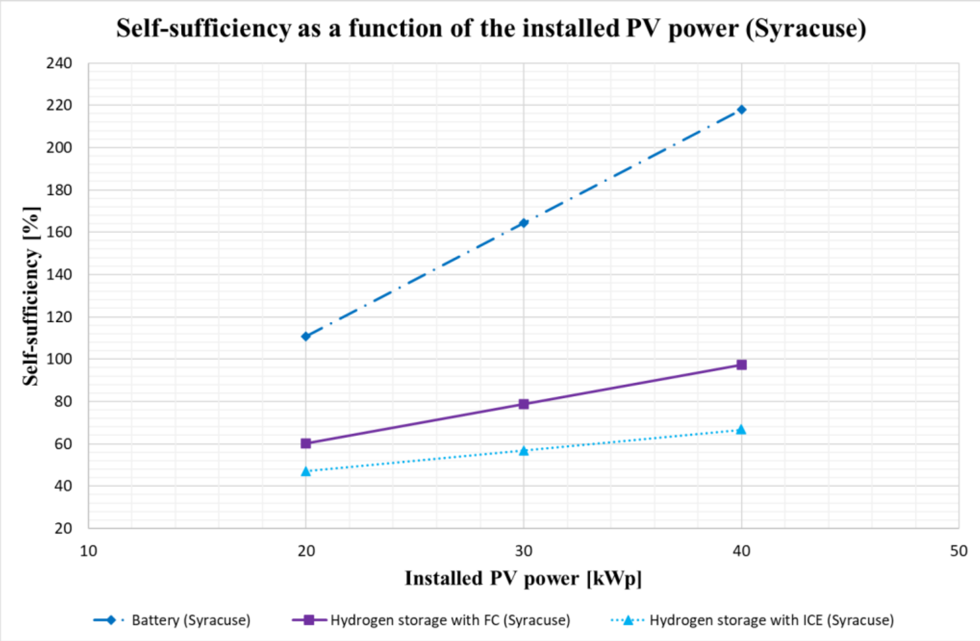

Figure 5.21. Electric Self-sufficiency of the system located in Syracuse.

Further, as in the case of Rome, the self-sufficiency of the PV system with the battery located in Syracuse is higher than 100% also at 20 kW_p of installed power. Instead, also in the case of Syracuse, the PV plant with the hydrogen storage system presents an electric self-sufficiency lower than 100% in all considered cases.

Also concern the overall parameters, the consideration that have been made in the case of the plants located in Rome and Milan are valid in that of Syracuse, as it is shown in the Figure 5.22. and Figure 5.23.

As expected, both the overall self-sufficiency and the overall efficiency of the plant located in Syracuse present higher values than those of the plant located in Rome and Milan, at the same installed PV power. In general, this is due to the higher percentage of covered thermal energy by the SWH located in Syracuse. Further, in the case of the hydrogen storage system, a higher value of electrical storable energy during the day means a higher hydrogen production by the electrolyser and consequently a higher value of recovered thermal energy from this. Moreover, a higher production of hydrogen also means that both the FC and the ICE can produce a higher quantity of energy, both from the electrical and thermal point of view.

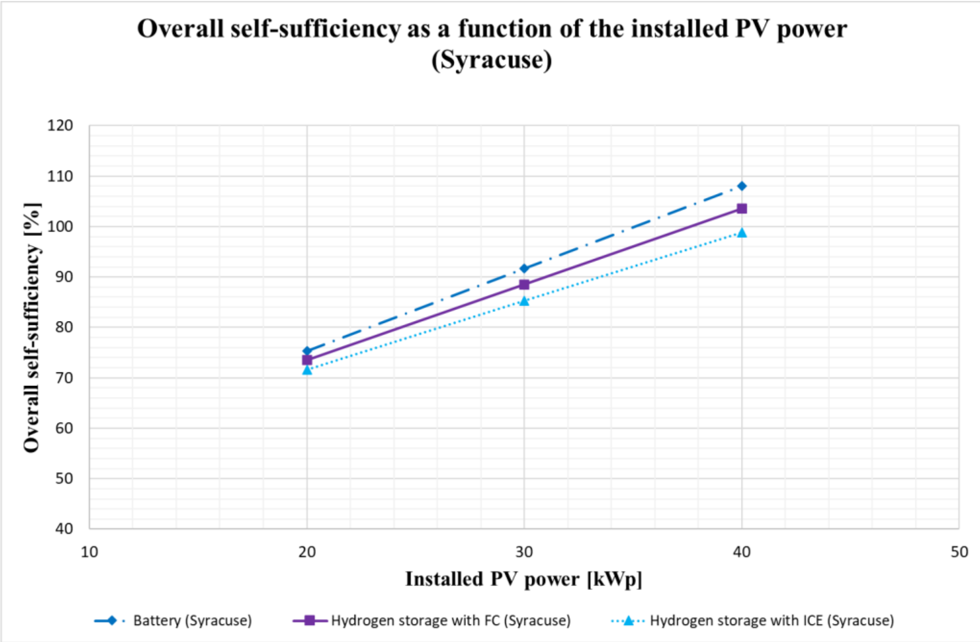

Figure 5.22. Overall self-sufficiency of the system located in Syracuse.

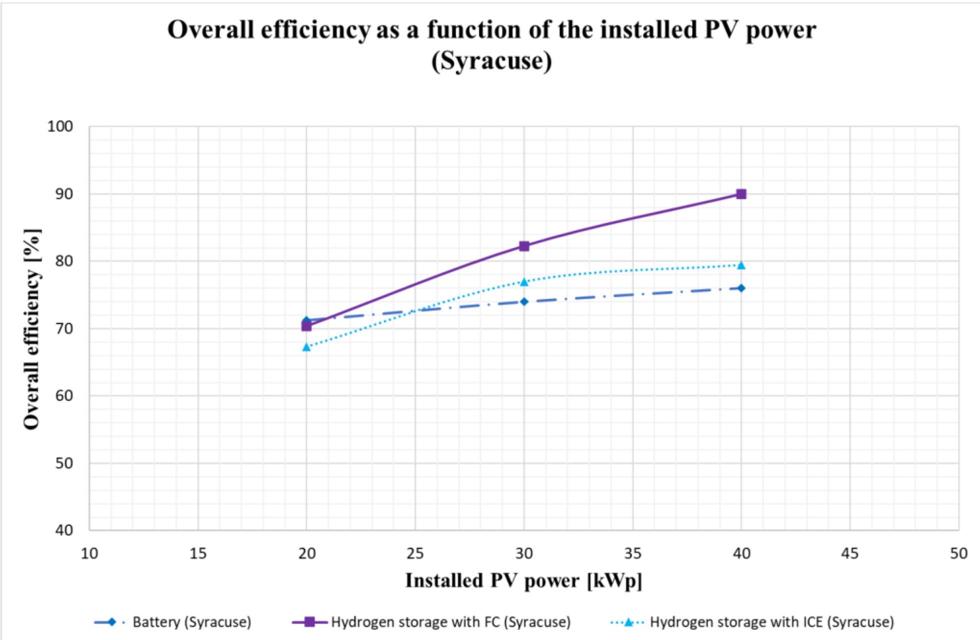

Figure 5.23. Overall efficiency of the system located in Syracuse.

However, also in this case, the increasing of the recovered thermal energy generates a gain until a certain point. Indeed, both the overall efficiencies of the plants with the hydrogen storage system present a non-linear trend. This is due to the exceeding amount of recovered thermal energy by the hydrogen storage system with respect the required one by the end users that cannot be used to the DHW. Therefore, this generates a loss of thermal energy that grows increasing the installed PV power that imply a penalty in the overall efficiency. This penalty is as accentuated as higher the amount of recovered thermal energy that has been lost.

It can be observed that the overall efficiency in the case of plant with battery located in Syracuse presents a lower slope of the line with respect to the case of the same plant located in Rome and Milan. This is mainly due to the higher energy production (both electric and thermic) while the users needs remain the same

5.5. Discussion of the obtained results by the energy balance on annual base

Once all the cases have been analyzed, a first conclusions as concern the main performance parameters on annual base Could be deduced. As expected, these plants shown better performances in Syracuse, then in Rome and at the end in Milan, due to longer availability if sun.

It is possible to say that from the electrical point of view the plants with battery have better performances with respect those with the hydrogen storage system, at the same installed PV power.

However, considering the overall energy balance the situation is quite different. Indeed, to recover thermal energy from the plants with hydrogen storage system gives the possibility to make competitive these kinds of system with respect those with battery. In this regard, as concern the overall self-sufficiency, the gap of values at the same installed PV power is strongly reduced with respect the electrical self-sufficiency. Nevertheless, the values of the overall self-sufficiency in the case of the plants with battery are in any cases higher than those with the hydrogen storage system. While, considering the overall efficiency, its value is higher in the case of 20 kW_p of installed PV plant with battery with respect the case with the hydrogen storage system. Increasing the installed PV power, the values of the overall efficiency in the case of the plants with the hydrogen storage systems becomes higher than those with battery. This is due to the higher amount of recovered thermal energy that generates a gain for this kind of plants. In any case, the overall efficiency has a linear trend until all the recovered thermal energy can be used to satisfy the required thermal energy by the end users. After that, the overall efficiency has a non-linear trend because the exceeding amount of energy cannot be used. This represents a loss of thermal energy that generates in some cases a penalty. In any case, also considering the overall parameters, the location that shows better performances is Syracuse, then Rome and at the end Milan.

Therefore, in this chapter has been obtained that the PV plant with the hydrogen storage systems can be competitive with respect those with battery. However, this is valid starting from a certain value of the installed PV power and it is strongly dependent from the chosen location.

But yearly averages do not consider the seasonal variation of the energy production. So that, to be closer to real applications, the analysis has been also carried out considering a monthly energy balance.

6. Energy balance on monthly base of reference home systems: general case

Once the results given by the energy balance on annual base have shown the possibility of the hydrogen storage systems to become competitive with respect the battery, in this chapter the energy balance on monthly base is carried out. This is carried out by considering the same design parameter of the components of the different systems. In this way, it is possible to obtain a more accurate result of the performances parameters. Indeed, the seasonal variations of the produced electric energy by the PV and the required one by the users are possible to be considered. These trends are respectively shown in the Figure 6.1. and Figure 6.2.

The first one is obtained by considering a 20 kW_p PV plant installed in Milan. As well know the produced energy by the PV plant reaches the highest value during the summertime, while the lowest one during the winter, both due to contribution of solar irradiance and weather changes.

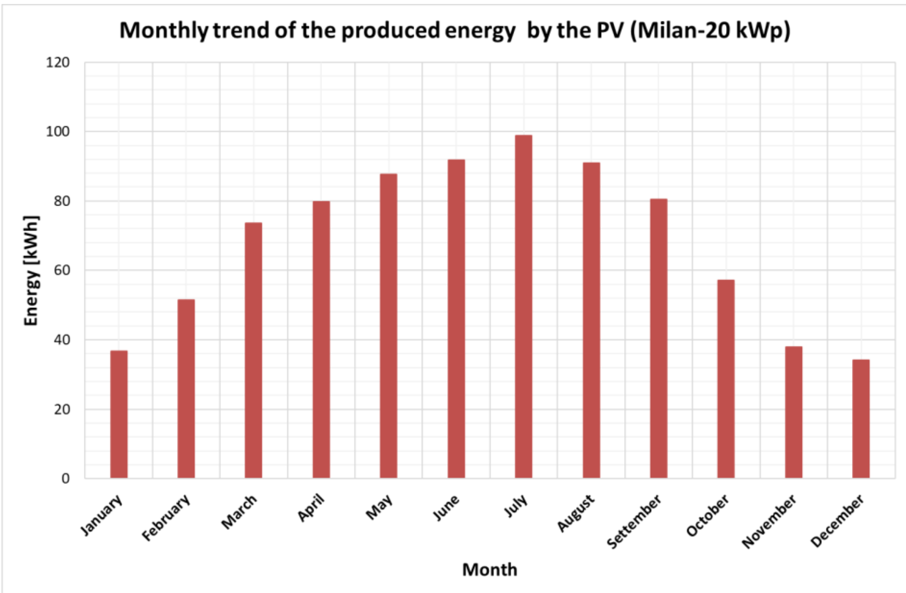

Figure 6.1. Seasonal variations of the produced EE.

The plot in Figure 6.2. is obtained by considering a sample of the monthly EE consumption of the Italian families. This shows that the monthly trend of the daily required EE by the users reaches the highest values both during the winter and the summer. This is due to the air conditioning of the living spaces. While the lowest values are reached both during the spring and autumn.

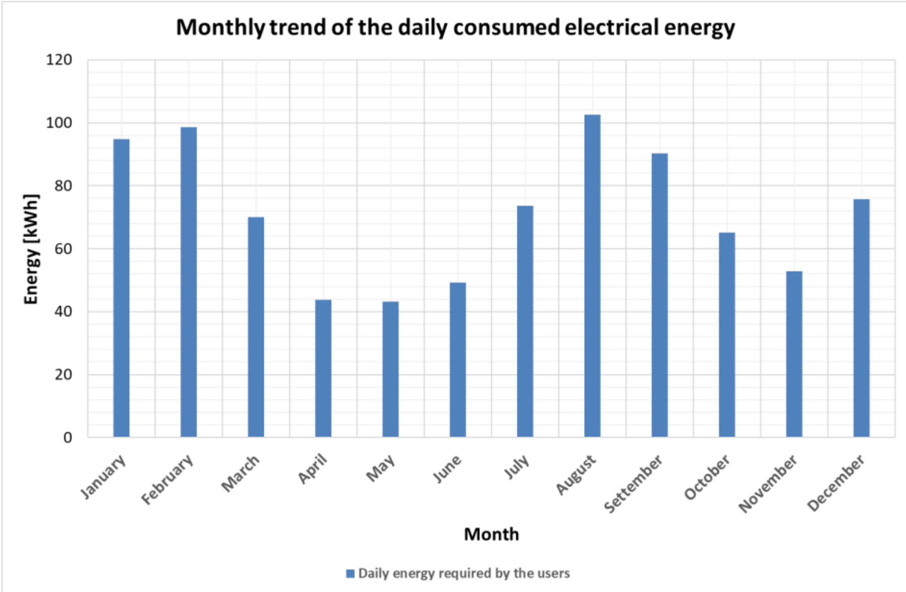

Figure 6.2. Seasonal variations of the daily consumed EE.

Compairing the two figures, it is possible to notice that a high level of exceeding amount of energy could be possible to be stored during the spring/summer period. This phenomenon will be more evident by increasing the PV power and by considering the plant installed in Rome or Syracuse. However, the amount of energy that could be stored depends on the considered storage system.

Thus, as concern the hydrogen storage system, the possibility of the seasonal storage of the hydrogen into the metal hydrides tank can be now considered. Indeed, it is expected that during the spring/summer, the produced EE by the PV is sufficient to satisfy the required one by the users during the day. Further, the exceeding amount of electrical energy can be used by the electrolyzer to produce hydrogen, as represented in the Figure 6.3. The produced hydrogen is then used by the FC/ICE to be converted again into electrical energy to fully satisfy the required one by the users during the night. Further, despite the losses, an exceeding amount of hydrogen can be predicted, due to the high electrical production with respect the consumption, as shown in the Figure 6.3. This is then stored into the metal hydrides tank to be used in the following months, decreasing the needing of the imported energy by the grid. In this way, in some cases the application of the maximum storage capability will be justified. However, also in analysis this design parameter will result oversized in some cases, because the produced hydrogen will not be sufficient to fully fill the storage system. Despite the possibility of the oversizing, this is one of the main advantages of this kind of storage technology, that could generate an increasing of the performance parameters.

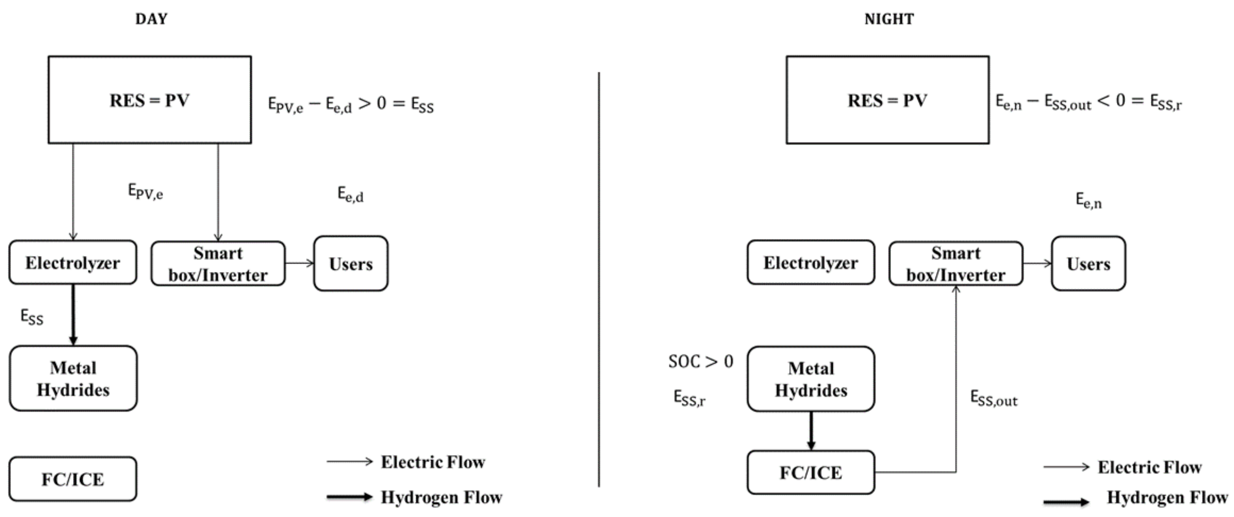

Figure 6.3. Typical EE balance on a spring/summer day.

Instead, as concern the battery, if the energy that is stored during the day and released during the night is higher than the energy consumed by the users, the exceeding amount could be used in the following days. However, once the seasonal variations are taken into account, also the low probability of cloudy/raining days has to be considered during this period of the year, depending on the location. Thus, this exceeding amount of EE might not be used in a short period of time. This means that if in the following days, a further exceeding amount of EE is produced, this cannot be stored, since the SOC of the battery is already at a high level. Thus, this energy has to be exported. To overcome this problem and to consider the battery as a seasonal storage, it could be possible to oversize the capacity of the battery. However, batteries suffer of some parasitic effects that can damage their storage capability if not used for long time. For this reason, this kind of device is not advised for the seasonal storage and it is preferable to export the energy to the grid.

Now, considering the TE balance, the design of the SWH system is maintained unchanged from the previous analysis. Further, the daily thermal energy that the SWH system is able to release is considered constant during the year and equal to that used in the previous analysis, depending on the considered location. This approximates the real case, as also the SWH system produces energy depending on the weather conditions. However, the purpose of the thesis is mainly focused on the electrical balance, thus this approximation has been considered acceptable.

In addition, also the design of the electrical storage systems is considered unchanged. Thus, the monthly analysis is applied on the basis of these criteria. In this way, it is possible to do a suitable comparison of new results with those obtained in the previous chapter. Therefore, fixing the storage size, the energy flows are function of the monthly variations only, while all the other input parameters are the same of the previous cases. Starting from the analysis of the different situations that can occur is possible to apply the energy balance on monthly base. An optimization of the storage size according to the monthly behavior of the green energy production is out of the thesis scope and will be the argument of future works.

6.1. Description of the energy balance on monthly base

So long as the aim of the energy balance on monthly base is to obtain a more detailed result of the performance parameters of the system, in in the follow the storage size (S_b) is considered an input parameter given by the result obtained on annual base, each in the respective case. In this way, it is possible to consider unchanged the characteristic of each system, while the seasonal variations of the produced electric energy and the consumed one are considered as inputs. Thus, the aim of this paragraph is to highlight all the considerations that can be made for the energy balance on monthly base.

First, since in the previous analysis the PV plant was designed to satisfy the daily consumed energy during the day, it is expected that, on average, a given amount of EE can be stored during the day to be released during the night. However, the EE that can be stored depends on the size of the storage system (S_b) and its SOC, and in the case of battery is considered the DOD that reduces the maximum storable EE ($E_{ss,max}$). Thus, different electrical energy flows between the PV plant, the storage system, the end users and the grid during the day can be analyzed:

- $E_s < E_{ss,max}$ and $SOC < SOC_{max}$, the EE surplus during the light hours (E_s) is totally stored, represented in the Figure 5.5. (Page 53). This is a typical autumn/winter situation, during which the electrical energy production is low, then the exceeding amount of energy during the day is totally stored. Thus, the storage system results oversized with respect the energy production.
- $E_s > E_{ss,max}$ and the $SOC < SOC_{max}$, the energy surplus during the day is partially stored, until the SOC becomes equal to the SOC_{max}, and then it is exported to the grid, as plotted in the Figure 5.6. (Page 53) This is a typical spring/summer situation, during which the electrical energy production is high, thus the exceeding amount of energy during the sun hours cannot fully stored.
- $SOC = SOC_{max}$, the energy surplus produced during the sun hours is fully exported to the grid, as represented in the Figure 5.7. (Page 54) This is a typical spring/summer situation, and it has to be matched with the following condition:

  $E_{e,n} - E_{ss,out} < 0 = E_{ss,r}$ thus, the energy stored net of losses fully meets the nightly energy consumption. In principle, the excess of energy could be used for the next days, but due to SOC saturation it is not possible to store it. This situation occurs because of the high electrical energy production and the low probability of cloudy/raining day during the spring/summer. However, this last condition occurs only in Rome, from June to August, and Syracuse, from May to October, but with different behaviors for the two considered storage system:

- As concern the battery, during these months, the weather condition does not allow to use the reserve of energy in the following days, generating a saturation of the storable energy. So that, batteries work between SOC_{max} and $SOC_{max} - E_{e,n}$. This means that the only amount of energy that can be really stored during the day correspond to that consumed during the night ($E_{e,n}$). Therefore, the rest of the produced energy by the PV must be exported to the grid, or we need to largely increase the size of batteries.
- As concern the hydrogen storage systems, as a difference with the battery, the energy reserve is represented by a certain hydrogen mass that is stored into the metal hydrides tank. However, if this situation occurs for a certain period of time, also the metal hydrides tank achieves the saturation of the allocated 750 geometric liters tanks, corresponding to 27,72 kg of stored hydrogen (SOC_{max}). While, without changing the electrolyser size, extra storage could be created by adding metal hydrate bottles. Unlucky, this seasonal reserve of energy is limited by the today safety regulation in Italy, as already said. Consequently, also in this case the system will works between SOC_{max} and $SOC_{max} - E_{e,n}$, although the electrolyzer is able to produce much more hydrogen than that consumed during the night. Thus, the rest of the produced energy by the PV plant has to be exported to the grid.

Then, the different energy flows during the night are considered:

- $E_{e,n} - E_{ss,out} < 0 = E_{ss,r}$ thus, this situation refers to the aforementioned one, represented in Figure 5.8. (Page 56). This is a typical spring/summer situation. However, in this case, the possibility to generate the reserve of energy is considered, because the saturation condition has not already occurred.

Instead, as concern the TE balance, the same considerations of the previous chapter are applied. However, some differences are reported in the case of the hydrogen-based storage systems. Indeed, the recovered TE depends on the consumed electrical energy by the electrolyzer and produced one by the FC/hydrogen ICE. Thus, also the recovered waste heat follows a seasonal variation. Moreover, as seen before, in the case of saturation of the metal hydrides tanks, the energy that is really consumed by the electrolyzer and that produced by the FC/ICE is reduced. Consequently, also the required TE by the auxiliary boiler depends on the seasonal variations. These situations could generate an increasing or decreasing of the overall parameters, depending on the considered month.

Once the energy flows of the overall system are explained considering the seasonal variation, the energy balance on monthly base can be carried out. Thus, all the performance parameters explained in the chapter 5 have been calculated for each month of the year (Page 57 and 58). In the end, the final value is calculated through an average of monthly ones.

6.2. Analysis of 20 kW$_p$ PV plant with storage system: Milan

As in previous chapter, the starting point of the analysis is the case of Milan with 20kWp installed PV plant.

The daily average monthly produced EE by the PV plant, the consumed one by the families and their difference are calculated, as shown in the Figure 6.4.

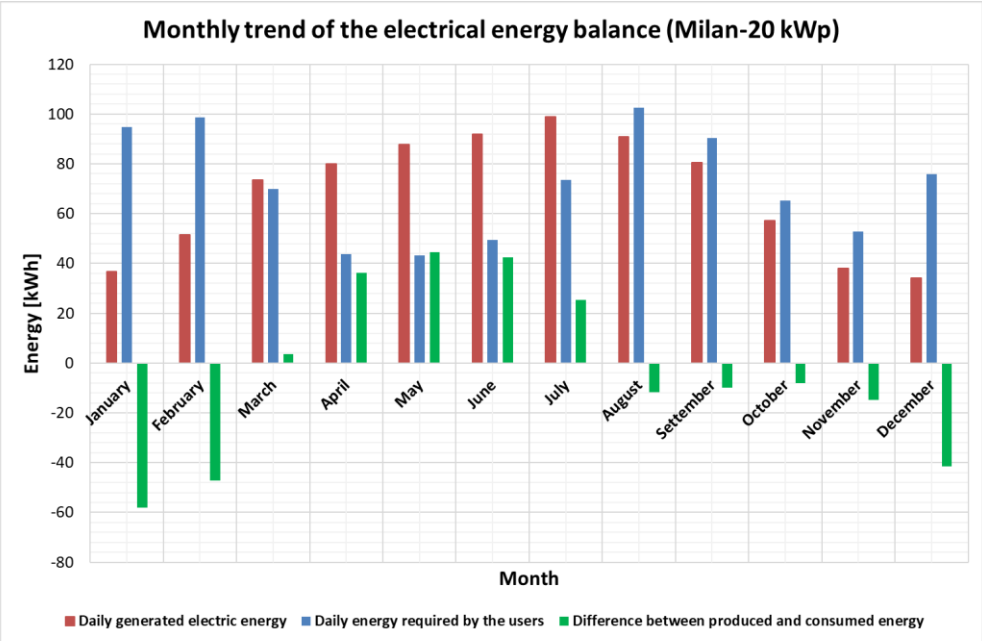

Figure 6.4. Produced EE, consumed one and their difference for 20 kWp of PV plant installed in Milan.

As expected, the first one presents the highest value during the summer periods, while the lowest ones during the winter. Thus, the difference between the produced EE and the consumed one presents a deficit during the winter, when the production is the lowest and the consumption is the highest, then a certain amount of EE has to be imported during the night from the grid. While this difference presents a surplus from March to July. Therefore, depending on the considered technology, this could mean that there is not the necessity to import energy during the night from the grid, during this period.

First, the monthly energy balance is applied in the case of the battery. From the results obtained in the previous analysis (Page 60), always considering the same input parameters, it is known that the battery size has to be equal to 63,68 kWh$_e$ (S_b). Therefore, the maximum storable EE is equal to 44,58 kWh$_e$/d ($E_{ss,max}$) and the outcoming one net of losses ($E_{ss,out}$) is equal to 38,11 kWh$_e$/d.

As said in the introduction chapter concerning the TE balance, the covered thermal energy by SWH system and thermal energy by the auxiliary boiler are assumed capable any time to satisfy the users, thus yearly averages are considered as a constant. On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.1. and showed in the Figure 6.5.

Table 6.1. Monthly energy balance of 20 kWp of PV plant with battery installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	20,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	36,68	51,46	73,55	79,88	87,77	91,79	98,87	90,97	80,43	57,11	38,00	34,19	[kWh/d]
Average produced EE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Battery size	63,68												[kWh]
EE balance													
Storable EE during the day	5,06	18,60	50,22	65,32	73,36	75,35	74,35	56,78	50,32	35,39	20,37	8,92	[kWh/d]
Real storable EE during the day	4,56	16,74	40,12	40,12	40,12	40,12	40,12	40,12	40,12	31,85	18,33	8,03	[kWh/d]
Stored EE (Round-trip efficiency)	4,33	15,90	38,11	38,11	38,11	38,11	38,11	38,11	38,11	30,26	17,41	7,63	[kWh/d]
Output of EE (Self-discharge)	20,01	37,90	67,39	67,39	67,39	67,39	67,39	67,39	67,39	54,67	33,66	22,25	[kWh/d]
EE defici/surplus (Night)	-58,90	-49,81	-8,55	9,00	9,30	5,22	-10,92	-30,27	-22,11	-13,18	-17,86	-42,91	[kWh/d]
Exported EE to the grid (Day)	0,00	0,00	5,64	20,75	28,78	30,77	29,78	12,20	5,75	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	35,94	48,76	61,45	52,67	52,52	54,56	62,63	72,31	68,22	51,98	35,05	32,90	[kWh/d]
Electrical self-Sufficiency	**37,90**	**49,47**	**87,78**	**120,62**	**121,51**	**110,59**	**85,15**	**70,49**	**75,53**	**79,77**	**66,25**	**43,40**	[kWh/d]
TE balance													
TE from the auxiliary boiler	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Overall efficiency	**45,44**	**49,29**	**60,56**	**63,71**	**64,84**	**65,39**	**63,68**	**58,36**	**58,50**	**57,17**	**53,23**	**47,66**	[%]
Overall self-sufficiency	**45,57**	**49,80**	**61,28**	**64,82**	**64,89**	**63,99**	**60,87**	**57,87**	**59,05**	**58,45**	**53,96**	**47,92**	[%]

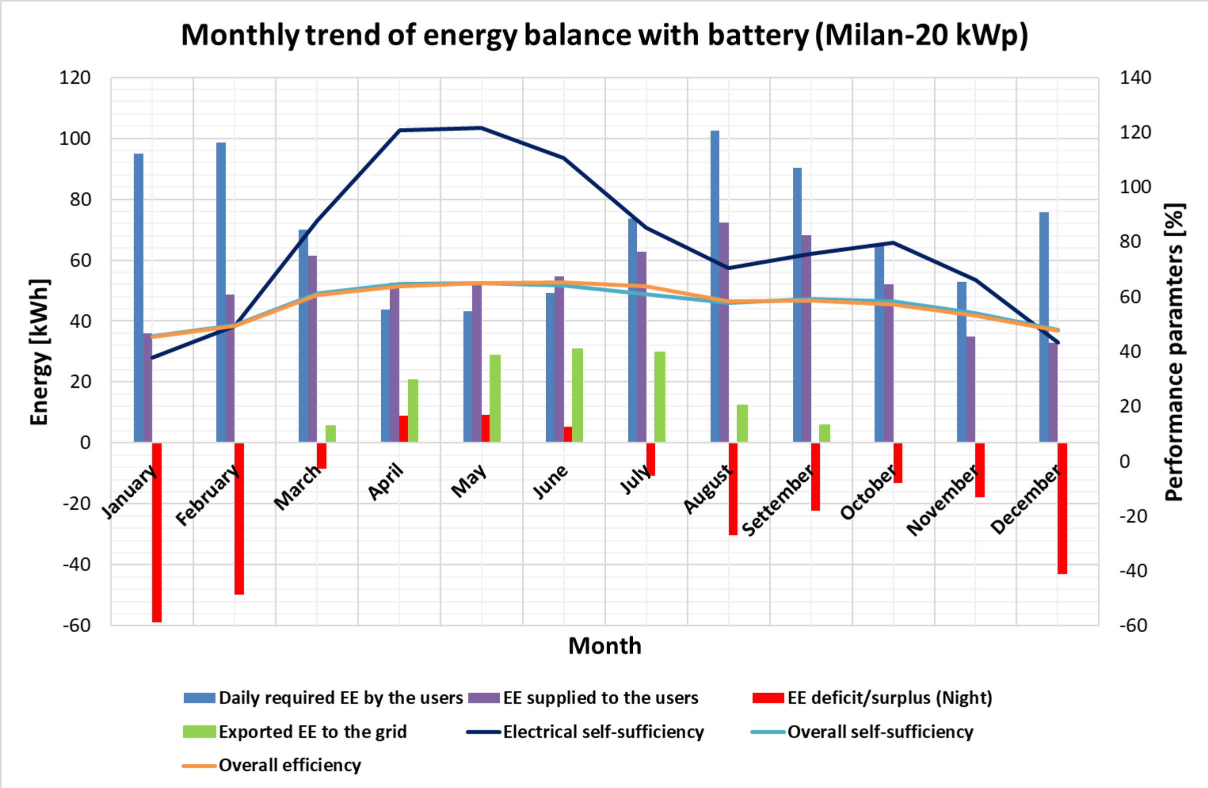

Figure 6.5. Monthly energy balance of 20 kWp of PV plant installed in Milan.

From these, it is possible to see that the produced EE by the PV plant is sufficient to meet the EE requirement during the day in autumn/winter period. The exceeding amount of EE is then stored into the battery (E_s) and released during the night ($E_{ss,out}$). However, this amount of energy is low compared with the other periods of the year, thus a certain amount of energy has to be imported from the grid. Consequently, both the EE supplied to the users and the electrical self-sufficiency reaches the lowest values, as expected. On the contrary, the produced EE by the PV plant reaches the highest values during the spring/summer period, thus the exceeding amount of electrical energy during the day is higher than the maximum storable energy. Consequently, the energy that cannot be stored is exported to the grid ($E_{e,g}$). In particular, the EE supplied to the users show the highest values during the summer, however the electrical self-sufficiency presents medium values due to the high EE requirement. The maximum electrical self-sufficiency is instead obtained from April to June, due to the lower EE requirement despite the medium values of the energy supplied to the users. During these months the value of the self-sufficiency is higher than 100%, thus the plant becomes independent from the grid. Further, in the case of Milan is considered that the exceeding amount of the stored EE with respect the energy consumed during the night can be used in the following days ($E_{ss,r}$), due to the high probability of cloudy/raining days, rather than to be exported to the grid. Then, the average values of the main performance parameters are obtained:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 52,42 kWh$_e$/d.

- The electrical self-sufficiency (SS) of the system results to be equals to 79,04%.
- The EE exchanged with the grid (E_g) in this case is equal to 21,21 kWh_e/d from imported from the grid ($E_{i,g}$) and 11,14 kWhe/d to be exported to the grid ($E_{e,g}$).

Also the average values of the main overall performance parameters are calculated:

- The overall self-sufficiency (SS_{oa}) is equal to around 57,37%.
- The overall efficiency (η_{oa}) is equal to around 57,32%.

Then, the monthly energy balance is applied in the case of hydrogen storage system with the fuel cell. Here, the electrolyzer size is equal to 14,4 kW_e, thus with a maximum EE consumption of 66,7 kWh_e/d ($E_{ss,max}$), as obtained in the previous analysis (Page 61). The metal hydrides tank has a geometrical volume equal to 750 l, as said in the previous chapter. Instead, the fuel cell size equal to 2,3 kW_e. This last device presents a size higher than that considered in the previous analysis, because it has to be able to produce a maximum EE equal to 20,81 kWh_e/d.

Instead, as a difference with the battery concerning the TE balance, the required TE by the boiler system depends on the recovered one both by the electrolyzer and the fuel cell. Thus, this depends on seasonal variations in the EE production by the PV plant. On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.2. and showed in the Figure 6.6.

Table 6.2. Monthly energy balance of 20 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
AverageEE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	20,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	36,68	51,46	73,55	79,88	87,77	91,79	98,87	90,97	80,43	57,11	38,00	34,19	[kWh/d]
Average produced EE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	14,40												[kW]
MH size (Geometrical volume)	750,00												[l]
Fuel cell size	2,30												[kW]
EE balance													
Theoretical storable EE during the day	5,06	18,60	50,22	65,32	73,36	75,35	74,35	56,78	50,32	35,39	20,37	8,92	[kWh/d]
Real storable EE during the day	5,06	18,60	44,58	44,58	66,70	66,70	66,70	44,58	44,58	35,39	20,37	8,92	[kWh/d]
Mass of produced hydrogen	0,09	0,35	0,94	1,22	1,25	1,25	1,25	1,06	0,94	0,66	0,38	0,17	[kWh/d]
Energy stored via hydrogen	3,16	11,61	31,34	40,77	41,63	41,63	41,63	35,44	31,41	22,09	12,71	5,57	[kWh/d]
Output of EE	1,58	5,80	15,67	20,38	20,81	20,81	20,81	17,72	15,70	11,04	6,36	2,78	[kWh/d]
EE deficit/surplus	-61,65	-59,91	-31,00	-8,73	-8,00	-12,07	-28,22	-50,67	-44,52	-32,40	-28,91	-47,75	[kWh/d]
Exported EE to the grid	0,00	0,00	0,00	0,00	6,66	8,65	7,65	0,00	0,00	0,00	0,00	0,00	[kWh/d]
Theoretical deficit/excess of H_2 (daily)	-3,70	-3,59	-1,86	-0,52	-0,48	-0,72	-1,69	-3,04	-2,67	-1,94	-1,73	-2,87	[kg]
Theoretical deficit/excess of H_2 (monthly	-114,67	-100,66	-57,66	-15,71	-14,89	-21,74	-52,49	-94,25	-80,14	-60,27	-52,05	-88,83	[kg]
Cumalated of H_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per month	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per day	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real EE surplus	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	33,19	38,66	39,00	34,94	35,22	37,26	45,33	51,91	45,81	32,76	23,99	28,05	[kWh/d]
Electrical self-Sufficiency	**35,00**	**39,22**	**55,72**	**80,02**	**81,49**	**75,52**	**61,63**	**50,61**	**50,72**	**50,28**	**45,35**	**37,01**	[kWh/d]
TE balance													
TE from the auxiliary boiler	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Recovered TE by the FC	1,58	5,80	15,67	20,38	20,81	20,81	20,81	17,72	15,70	11,04	6,36	2,78	[kWh/d]
Recovered TE by the electrolyzer	1,03	3,80	10,25	13,34	14,98	15,38	15,18	11,59	10,27	7,23	4,16	1,82	[kWh/d]
Total recovered TE	2,61	9,60	25,92	33,72	35,79	36,20	35,99	29,31	25,98	18,27	10,51	4,61	[kWh/d]
Overall efficiency	**45,44**	**49,29**	**60,56**	**63,71**	**64,84**	**65,39**	**63,68**	**58,36**	**58,50**	**57,17**	**53,23**	**47,66**	[%]
Overall self-sufficiency	**45,57**	**49,80**	**61,28**	**64,82**	**64,89**	**63,99**	**60,87**	**57,87**	**59,05**	**58,45**	**53,96**	**47,92**	[%]

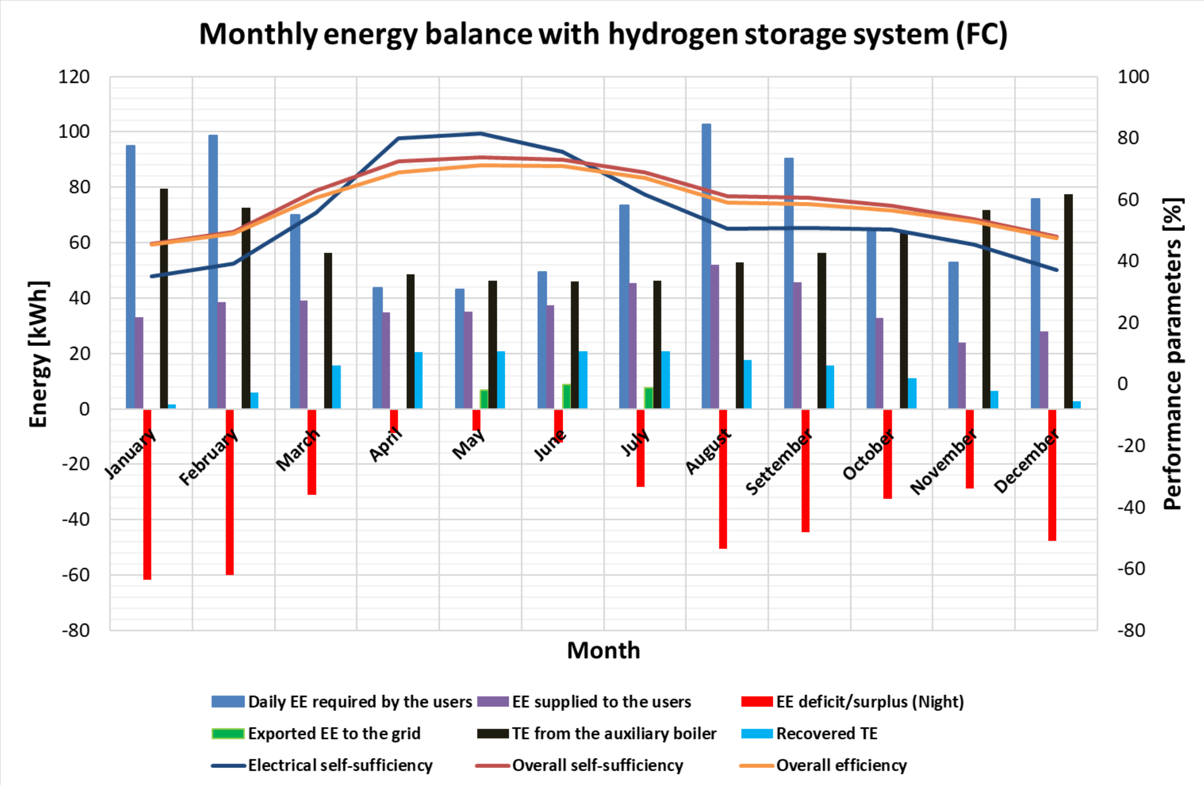

Figure 6.6. Monthly energy balance of 20 kWp of PV plant with hydrogen storage system installed in Milan.

From this, it is possible to see that the trend of the monthly EE balance is almost the same of the plant with battery. However, because of the lower electrical efficiency, the hydrogen storage system with fuel cell presents lower values of the EE supplied to the users and, consequently, of the electrical self-sufficiency. Consequently, despite the EE surplus from March to July showed in the Figure 6.5., the electric energy always needs to be imported from the grid, due to the higher energy losses during the storage process. This means that in this case, all the produced hydrogen during the day is consumed during the night, without the possibility of seasonal storage. Due to the higher maximum storable energy compared to the case of the battery, the energy exported to the grid is greatly reduced. Then, the values of the main electrical performance parameters are calculated:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 37,18 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 55,21%.
- The EE exchanged with the grid (E_g) in this case is equal to around 34,49 kWh_e/d of energy to be imported from the grid ($E_{i,g}$), and 1,91 kWh_e/d of energy to exported to the grid ($E_{e,g}$).

As concern the TE balance, the recovered TE increases with the increasing of the consumed EE by the electrolyzer and the produced one by the FC. Thus, this is lower during the autumn/winter months, when the available electricity is lower, compared to the spring/summer months, when the available electrical energy is higher. Consequently, the energy needed by the boiler system follows the opposite trend, thus:

- The overall self-sufficiency (SS_{oa}) is equal to around 60,58%.
- The overall efficiency (η_{oa}) is equal to around 58,93%.

At the end, the monthly energy balance is applied in the case of the hydrogen storage system with ICE. Here, both the electrolyzer and the metal hydrides tank size is always the same. While the ICE size is equal to 1,2 kW_e because it has to be able to produce a maximum EE equal to 10,82 kWh_e/d (Page 62).

As concern the TE balance, the covered thermal energy from the SWH system is always the same, while the thermal energy needed by the auxiliary boiler depends on the recovered one both by the electrolyzer and the ICE.

On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.3. and showed in the Figure 6.7.

Table 6.3. Monthly energy balance of 20 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
AvergareTE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	20,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	36,68	51,46	73,55	79,88	87,77	91,79	98,87	90,97	80,43	57,11	38,00	34,19	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	14,40												[kW]
MH size (Geometrical volume)	750,00												[l]
ICE size	1,20												[kW]
EE balance													
Theoretical storable EE during the day	5,06	18,60	50,22	65,32	73,36	75,35	74,35	56,78	50,32	35,39	20,37	8,92	[kWh/d]
Real storable EE during the day	5,06	18,60	44,58	44,58	66,70	66,70	66,70	44,58	44,58	35,39	20,37	8,92	[kWh/d]
Mass of produced hydrogen	0,09	0,35	0,94	1,22	1,25	1,25	1,25	1,06	0,94	0,66	0,38	0,17	[kWh/d]
Energy stored via hydrogen	3,16	11,61	31,34	40,77	41,63	41,63	41,63	35,44	31,41	22,09	12,71	5,57	[kWh/d]
Output of EE	0,82	3,02	8,15	10,60	10,82	10,82	10,82	9,21	8,17	5,74	3,30	1,45	[kWh/d]
EE deficit/surplus (Night)	-62,40	-62,70	-38,52	-18,51	-17,99	-22,07	-38,21	-59,17	-52,06	-37,70	-31,96	-49,09	[kWh/d]
Exported EE to the grid (Day)	0,00	0,00	0,00	0,00	6,66	8,65	7,65	0,00	0,00	0,00	0,00	0,00	[kWh/d]
Theoretical deficit/excess of H_2 (daily)	-7,20	-7,23	-4,44	-2,14	-2,08	-2,55	-4,41	-6,83	-6,01	-4,35	-3,69	-5,66	[kg]
Theoretical deficit/excess of H_2 (monthly	#####	#####	#####	-64,08	-64,37	-76,39	######	#####	#####	#####	#####	#####	[kg]
Cumalated of H_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per month	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per day	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real energy surplus	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	32,43	35,88	31,48	25,16	25,23	27,27	35,34	43,41	38,28	27,46	20,94	26,72	[kWh/d]
Electrical self-Sufficiency	**34,20**	**36,40**	**44,97**	**57,61**	**58,37**	**55,27**	**48,05**	**42,32**	**42,37**	**42,15**	**39,58**	**35,24**	[kWh/d]
TE balance													
TE from the auxiliary boiler	79,20	71,20	52,51	43,58	41,40	41,00	41,20	48,63	52,45	61,27	70,15	76,92	[kWh/d]
Recovered TE from the ICE	1,96	7,20	19,43	25,28	25,81	25,81	25,81	21,97	19,47	13,69	7,88	3,45	[kWh/d]
Recovered TE from the electrolyzer	1,03	3,80	10,25	13,34	14,98	15,38	15,18	11,59	10,27	7,23	4,16	1,82	[kWh/d]
Total recovered TE	2,99	10,99	29,68	38,61	40,79	41,19	40,99	33,56	29,75	20,92	12,04	5,28	[kWh/d]
Overall efficiency	**45,16**	**48,24**	**58,09**	**65,11**	**67,52**	**67,20**	**63,80**	**56,65**	**56,23**	**54,80**	**51,81**	**47,11**	[%]
Overall self-sufficiency	**45,37**	**49,08**	**61,16**	**70,16**	**71,39**	**70,49**	**66,62**	**59,62**	**58,97**	**56,88**	**53,00**	**47,54**	[%]

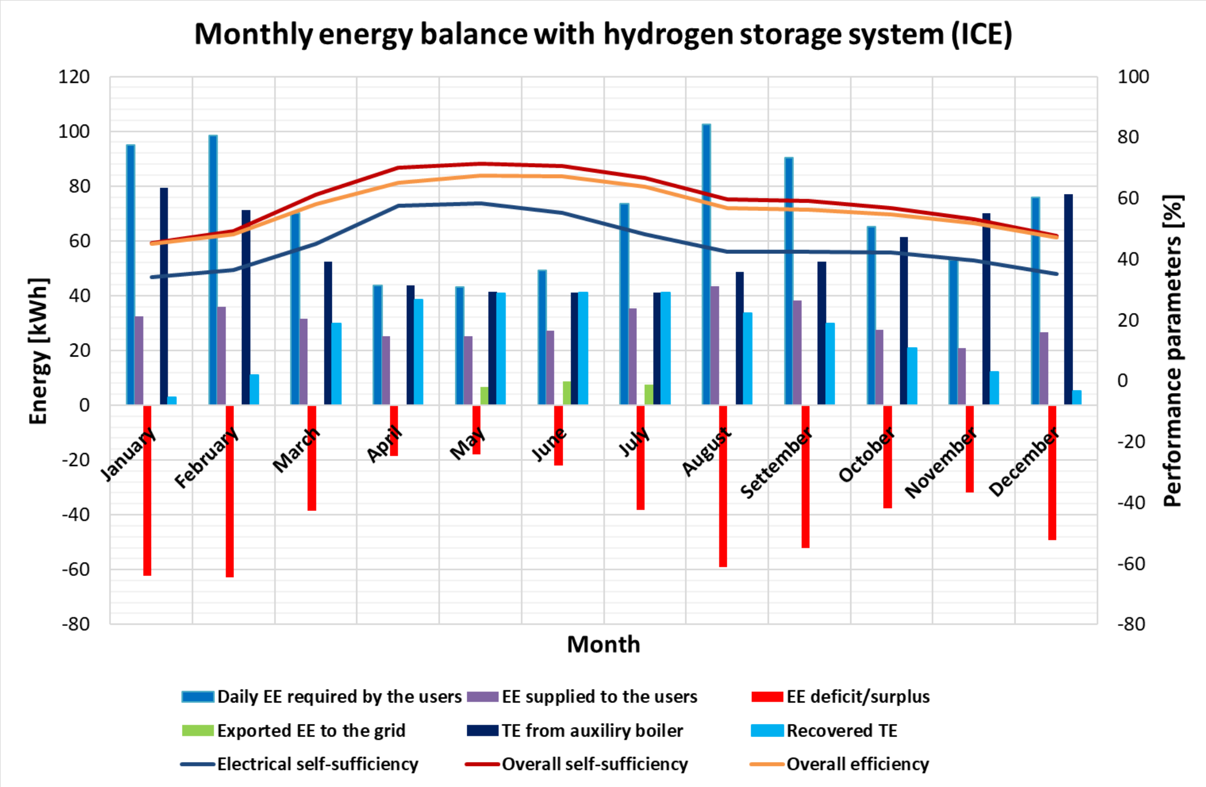

Figure 6.7. Monthly energy balance of 20 kW_p of PV plant with hydrogen storage system installed in Milan.

From this, it is possible to see that the trend of the monthly EE balance is almost the same than the plants with battery and hydrogen storage system with FC. However, due to the lowest value of the electrical efficiency compared to the other systems, the hydrogen storage system with ICE presents the lowest values of the EE supplied to the users and consequently the electrical self-sufficiency. Thus, in this case, despite the EE surplus from March to July, a higher amount of energy needs to be imported from the grid. This means that in this case, all the produced hydrogen during the day is consumed during the night, without the possibility of seasonal storage. Then:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 30,80 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 44,71%.
- The EE exchanged with the grid (E_g) in this case is equal to around 40,87 kWh_e/d of energy to be imported from the grid ($E_{i,g}$), and 1,91 kWh_e/d of energy to exported to the grid ($E_{e,g}$).

Also as concern the TE balance, the trend of the recovered thermal energy by both the electrolyzer and the ICE is almost the same than in the case with FC. However, thanks to the higher thermal efficiency of the ICE, the recovered waste heat is greater than in the case with the FC.

Thus, despite the lowest electrical efficiency of the system, the overall performance parameters in general present almost the same values of the plant with the battery. However, the plant with the FC always presents a better overall performance of the system. Thus, the average overall performance parameters are calculated:

- The overall self-sufficiency (SS_{oa}) is equal to around 59,19%.
- The overall efficiency (η_{oa}) is equal to around 56,81%.

6.2.1. Analysis of 30 kW$_p$ PV plant with storage system: Milan

Increasing to 30 kW$_p$ the value of the PV power, the average monthly produced EE per day from the PV plant, the consumed one per day by the families and their difference are calculated, as shown in the Figure 6.8. The first one presents a trend almost identical to that of the previous paragraph. However, by increasing the PV power, the average daily produced EE also increases. In this way, the difference between the produced EE and the consumed one reaches higher values, in the case of surplus of energy, or lower one, in the case of deficit of energy.

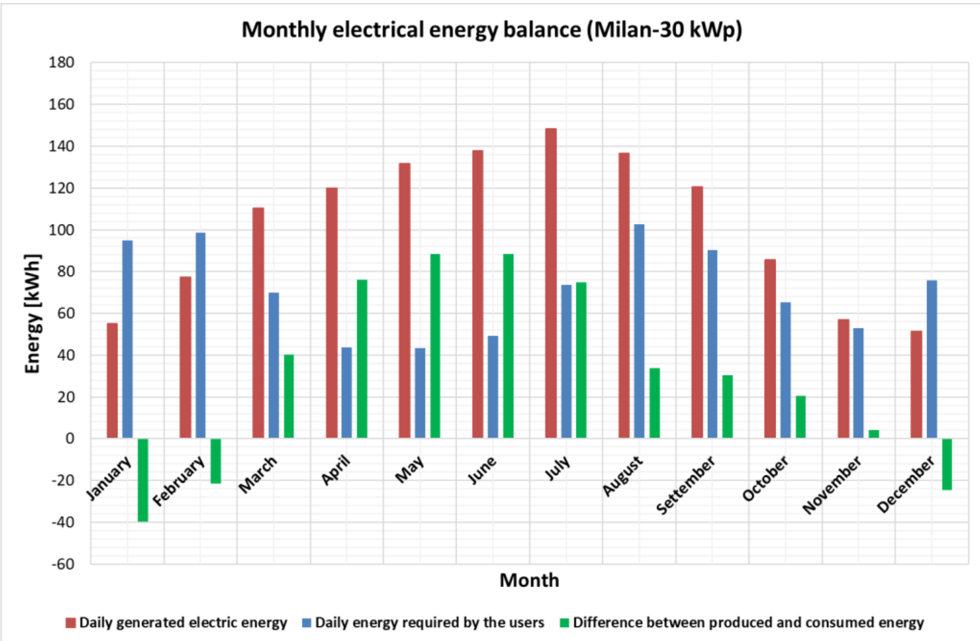

Figure 6.8. Produced EE, consumed one and their differences for 30 kWp of PV plant installed in Milan.

First, the monthly energy balance is applied in the case of the battery. From the results obtained in the previous analysis (Page 62), always considering the same input parameters, the battery size has to be equal to 112,60 kWh$_e$ (S_b). Therefore, the maximum storable EE is equal to 78,82 kWh$_e$/d ($E_{ss,max}$) and the outcoming one net of losses ($E_{ss,out}$) is equal to 67,39 kWh$_e$/d. Instead, the TE balance is considered unchanged.

On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.4. and plotted in the Figure 6.9.

Table 6.4. Monthly energy balance of 30 kWp of PV plant with battery installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	30,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	55,02	77,19	110,32	119,82	131,65	137,69	148,31	136,46	120,65	85,66	57,00	51,29	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Battery size	112,60												[kWh]
EE balance													
Theoretical storable EE during the day	23,40	44,33	86,99	105,26	117,24	121,25	123,79	102,27	90,54	63,94	39,37	26,02	[kWh/d]
Real storable EE during the day	23,40	44,33	78,82	78,82	78,82	78,82	78,82	78,82	78,82	63,94	39,37	26,02	[kWh/d]
Stored EE (Round-trip efficiency)	21,06	39,90	70,94	70,94	70,94	70,94	70,94	70,94	70,94	57,55	35,43	23,42	[kWh/d]
Output of EE (Self-discharge)	20,01	37,90	67,39	67,39	67,39	67,39	67,39	67,39	67,39	54,67	33,66	22,25	[kWh/d]
EE deficit/surplus	-43,22	-27,81	20,72	38,28	38,57	34,50	18,36	-1,00	7,17	11,23	-1,61	-28,29	[kWh/d]
Exported EE to the grid	0,00	0,00	8,17	26,44	38,42	42,43	44,97	23,45	11,72	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	51,62	70,76	90,72	81,95	81,80	83,84	91,91	101,58	97,50	76,39	51,29	47,52	[kWh/d]
Electrical self-Sufficiency	**54,43**	**71,78**	**129,61**	**187,66**	**189,24**	**169,94**	**124,96**	**99,03**	**107,94**	**117,24**	**96,95**	**62,68**	[kWh/d]
TE balance													
TE from the auxiliary boiler	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Overall efficiency	**50,95**	**56,78**	**65,92**	**67,06**	**68,38**	**69,01**	**70,06**	**68,65**	**67,15**	**63,42**	**59,86**	**53,17**	[%]
Overall self-sufficiency	**51,62**	**58,17**	**73,77**	**78,89**	**78,99**	**77,69**	**73,17**	**68,84**	**70,55**	**69,09**	**61,43**	**54,00**	[%]

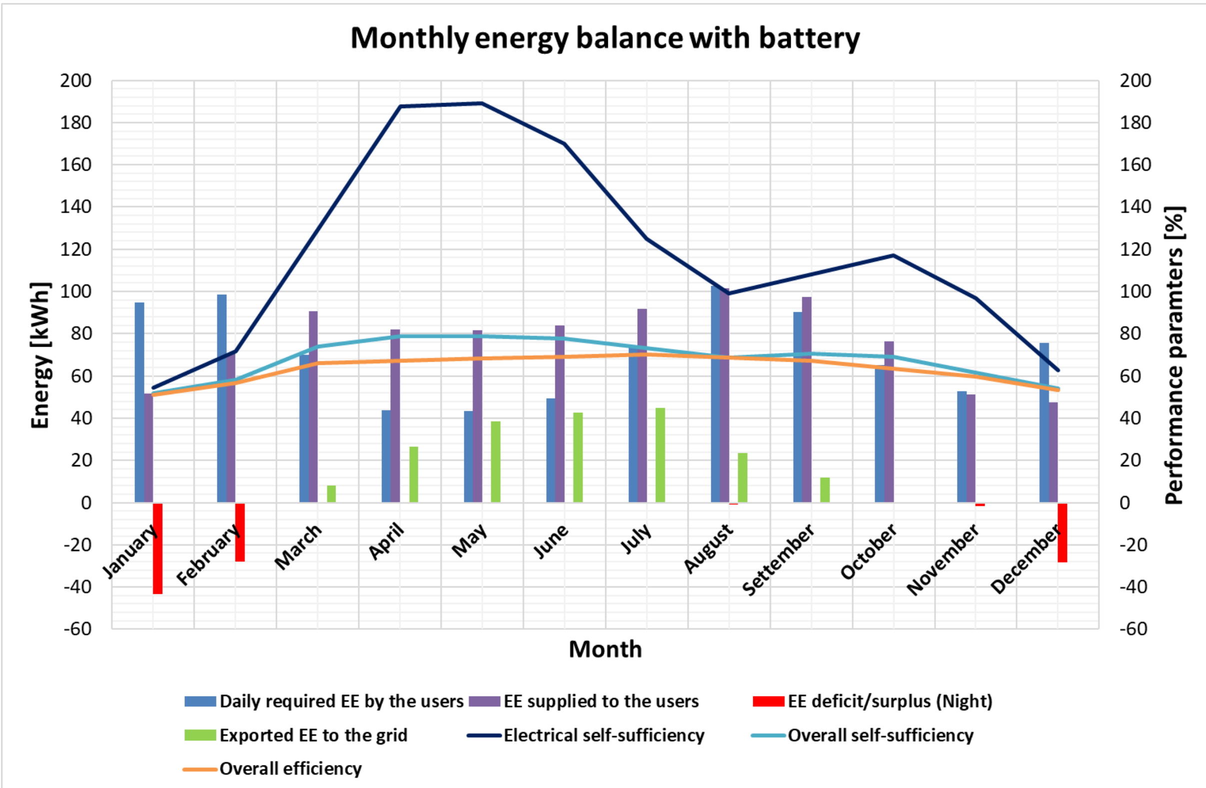

Figure 6.9. Monthly energy balance of 30 kWp of PV plant with battery installed in Milan.

It is possible to see that the trend of the results is similar to those obtained in the previous paragraph, always considering the battery as energy storage. However, thanks to the higher PV EE production, the storable EE (E_s) is higher than in the previous case, also during the autumn/winter. Consequently, both the outcoming EE net of losses ($E_{ss,out}$) and the EE supplied to the users (E_{s-u}) are higher. Furthermore, this electric energy is sufficient in some cases to meet the required electricity by the users during this period. Then, the EE that has to be imported by the grid during the night is lower. This is hugely highlighted during the autumn, while a high amount of energy is always required from the grid during the winter. Instead, considering the spring/summer period, the EE supplied to the users and consequently the electrical self-sufficiency present on average higher values. Indeed, the value of the electrical self-sufficiency is always higher than 100%. This means that the plant is always independent by the grid and a higher reserve of energy can be generated for the following days. Further, also the energy exported to the grid during this period is increased. Thus,

- The EE supplied to the users (E_{s-u}) results to be equal to 77,24 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 117,62%.
- The EE exchanged with the grid (E_g) in this case is equal to 8,49 kWh_e/d from imported from the grid ($E_{i,g}$) and 16,30 kWh_e/d to be exported to the grid ($E_{e,g}$).

Also the overall performance parameters present the same trend obtained in the previous paragraph. However, these reach on average higher values than those obtained previously, indeed:

- The overall self-sufficiency (SS_{oa}) is equal to around 68,02%.
- The overall efficiency (η_{oa}) is equal to around 63,37%.

Then, the monthly energy balance is applied in the case of hydrogen storage system with the fuel cell. In this case, the electrolyzer size is equal to 24 kW_e, thus with a maximum EE consumption of 111,17 kWh_e/d ($E_{ss,max}$) (Page 63). The geometrical volume of the metal hydrides tank is considered always the same. While the fuel cell size equal to 3,85 kW_e, with a maximum output of energy equal to 34,69 kWh_e/d.

Instead, as concern the TE balance, the covered thermal energy from the SWH system is always the same, while the thermal energy from the auxiliary boiler depends on the recovered one from the electrolyzer and the fuel cell. On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.5. and showed in the Figure 6.10.

Table 6.5. Monthly energy balance of 30 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	30,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	36,68	51,46	73,55	79,88	87,77	91,79	98,87	90,97	80,43	57,11	38,00	34,19	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	24,00												[kW]
MH size (Geometrical volume)	750,00												[l]
Fuel cell size	3,85												[kW]
EE balance													
Theoretical storable EE during the day	23,40	44,33	86,99	105,26	117,24	121,25	123,79	102,27	90,54	63,94	39,37	26,02	[kWh/d]
Real storable EE during the day	23,40	44,33	86,99	105,26	111,17	111,17	111,17	102,27	90,54	63,94	39,37	26,02	[kWh/d]
Mass of produced hydrogen	0,44	0,83	1,63	1,97	2,08	2,08	2,08	1,91	1,70	1,20	0,74	0,49	[kWh/d]
Energy stored via hydrogen	14,61	27,67	54,29	65,70	69,38	69,38	69,38	63,83	56,51	39,91	24,57	16,24	[kWh/d]
Output of EE	7,30	13,83	27,15	32,85	34,69	34,69	34,69	31,91	28,25	19,95	12,28	8,12	[kWh/d]
EE deficit/surplus	-55,92	-51,88	-19,52	3,74	5,87	1,80	-14,34	-36,47	-31,97	-23,49	-22,98	-42,42	[kWh/d]
Exported EE to the grid	0	0	0	0	6,08	10,08	12,62	0	0	0	0	0	[kWh/d]
Theoretical def./exc. of H_2 (daily)	-3,36	-3,11	-1,17	0,22	0,35	0,11	-0,86	-2,19	-1,92	-1,41	-1,38	-2,55	[kg]
Theoretical def./exc. of H_2 (monthly)	#####	-87,17	-36,31	6,73	10,92	3,24	-26,68	-67,85	-57,55	-43,69	-41,38	-78,90	[kg]
Cumalated of H_2	0	0	0	6,73	17,65	20,89	0	0	0	0	0	0	[kg]
Real excess of H_2 per month	0	0	0	6,73	10,92	3,24	0	0	0	0	0	0	[kg]
Real excess of H_2 per day	0	0	0	0,22	0,35	0,11	0	0	0	0	0	0	[kg]
Real energy surplus	0	0	0	3,74	5,87	1,80	0	0	0	0	0	0	[kWh/d]
EE supplied to the users	38,92	46,69	50,48	47,40	49,10	51,13	59,21	66,11	58,36	41,67	29,92	33,39	[kWh/d]
Electrical self-Sufficiency	**41,03**	**47,37**	**72,11**	**108,56**	**113,59**	**103,65**	**80,50**	**64,44**	**64,61**	**63,96**	**56,55**	**44,04**	[kWh/d]
TE balance													
TE from the auxiliary boiler	70,11	59,31	37,29	27,85	23,56	22,75	22,23	29,40	35,45	49,18	61,87	68,76	[kWh/d]
Recovered TE from the FC	7,30	13,83	27,15	32,85	34,69	34,69	34,69	31,91	28,25	19,95	12,28	8,12	[kWh/d]
Recovered TE from the electrolyzer	4,78	9,05	17,76	21,49	23,94	24,75	25,27	20,88	18,49	13,06	8,04	5,31	[kWh/d]
Total recovered TE	12,08	22,88	44,91	54,34	58,63	59,44	59,96	52,79	46,74	33,01	20,32	13,43	[kWh/d]
Overall efficiency	**50,60**	**56,09**	**71,22**	**80,02**	**82,56**	**83,60**	**80,12**	**70,68**	**69,30**	**65,22**	**59,11**	**52,73**	[%]
Overall self-sufficiency	**51,38**	**57,72**	**75,76**	**88,41**	**91,48**	**90,20**	**84,63**	**75,32**	**73,53**	**68,34**	**60,95**	**53,71**	[%]

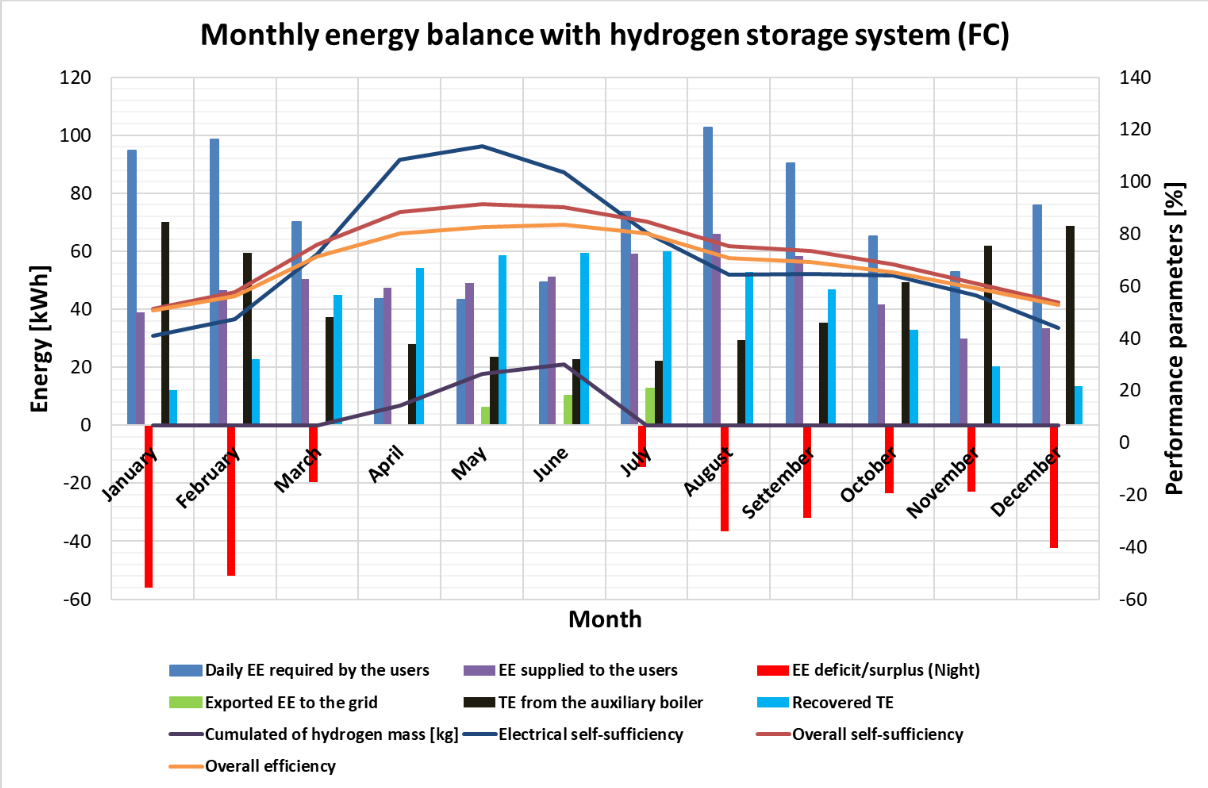

Figure 6.10. Monthly energy balance of 30 kWp of PV plant with hydrogen storage system installed in Milan.

Also for this sytem the trend of the monthly EE balance is almost the same of that for 20kW$_p$ PV case. However, due to the higher installed PV power and consequently the higher produced EE, the EE supplied to the users and the electrical self-sufficiency show on average higher values, while the energy imported from the grid shows lower ones. Moreover, due to this higher energy production from the PV plant, from April to June, the output of EE from the storage system is higher than the EE required during the night. This means that the exceeding hydrogen mass can be cumulated. This is used in the following days/months to compensate the energy that should be imported from the grid during the night. In this case, 20,89 kg$_{H2}$ of hydrogen are stored corresponding to 696,26 kWh$_{ch}$ of chemical energy to be used in the following months. This generates an increasing of both the EE supplied to the end users and the electrical self-sufficiency. However, to simplify the analytical problem, the stored hydrogen has been considered as consumed in the same production month, thus reaching values of the self-sufficiency higher than 100%. In the realty, the hydrogen consumption will be distributed during the winter/autumn. Then, the values of the main electrical performance parameters are obtained:

- The EE supplied to the users (E_{s-u}) results to be equal to 47,70 kWh$_e$/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 71,70%.
- The EE exchanged with the grid (E_g) in this case is equal to around 24,92 kWh$_e$/d of energy to be imported from the grid ($E_{i,g}$), and 2,40 kWh$_e$/d of energy to exported to the grid ($E_{e,g}$).

As a consequence of the higher EE production from the PV plant, a higher energy consumption by the electrolyser and a higher energy production by the fuel cell is get. This corresponds on average to a greater recoverable TE, thus decreasing that required by the boiler. Thus, the overall performance parameters always show almost identical trend with respect to the other cases, although in general they present higher values. Thus:

- The overall self-sufficiency (SS_{oa}) is equal to around 72,62%.
- The overall efficiency (η_{oa}) is equal to around 68,44%.

At the end, the monthly energy balance is applied in the case of the hydrogen storage system with ICE. Here, both the electrolyzer size and the metal hydrides tanks size are the same of the previous energy analysis, while the ICE size is equal to 2 kW_e, with a maximum output of EE 18,04 kWh_e/d (Page 64). As concern the TE balance, the covered thermal energy from the SWH system is always the same, while the thermal energy from the auxiliary boiler depends on the recovered one by the electrolyzer and the ICE.

On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.6. and represented in the Figure 6.11.

Table 6.6. Monthly energy balance of 30 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average electrical energy consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	30,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	55,02	77,19	110,32	119,82	131,65	137,69	148,31	136,46	120,65	85,66	57,00	51,29	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	24,00												[kW]
MH size (Geometrical volume)	750,00												[l]
ICE size	2,00												[kW]
EE balance													
Theoretical storable EE during the day	23,40	44,33	86,99	105,26	117,24	121,25	123,79	102,27	90,54	63,94	39,37	26,02	[kWh/d]
Real storable EE during the day	23,40	44,33	86,99	105,26	111,17	111,17	111,17	102,27	90,54	63,94	39,37	26,02	[kWh/d]
Mass of produced hydrogen	0,44	0,83	1,63	1,97	2,08	2,08	2,08	1,91	1,70	1,20	0,74	0,49	[kWh/d]
Energy stored via hydrogen	14,61	27,67	54,29	65,70	69,38	69,38	69,38	63,83	56,51	39,91	24,57	16,24	[kWh/d]
Output of EE	3,80	7,19	14,12	17,08	18,04	18,04	18,04	16,59	14,69	10,38	6,39	4,22	[kWh/d]
EE deficit/surplus	-59,43	-58,52	-32,55	-12,03	-10,78	-14,85	-30,99	-51,79	-45,53	-33,06	-28,88	-46,32	[kWh/d]
Exported EE to the grid	0,00	0,00	0,00	0,00	6,08	10,08	12,62	0,00	0,00	0,00	0,00	0,00	[kWh/d]
Theoretical def./exc. of H_2 (daily)	-6,86	-6,75	-3,76	-1,39	-1,24	-1,71	-3,58	-5,98	-5,25	-3,82	-3,33	-5,34	[kg]
Theoretical def./exc. of H_2 (monthly)	#####	#####	#####	-41,65	-38,56	-51,41	######	-185,3	#####	#####	-99,98	#####	[kg]
Cumalated of H_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per month	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real excess of H_2 per day	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kg]
Real energy surplus	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	35,41	40,05	37,45	31,64	32,45	34,48	42,55	50,79	44,80	32,10	24,02	29,49	[kWh/d]
Electrical self-Sufficiency	**37,34**	**40,63**	**53,50**	**72,45**	**75,06**	**69,90**	**57,86**	**49,51**	**49,60**	**49,26**	**45,41**	**38,90**	[kWh/d]
TE balance													
TE from the auxiliary boiler	68,36	55,99	30,77	19,97	15,24	14,42	13,90	21,74	28,67	44,39	58,92	66,81	[kWh/d]
Recovered TE from the ICE	9,06	17,15	33,66	40,73	43,02	43,02	43,02	39,57	35,03	24,74	15,23	10,07	[kWh/d]
Recovered TE from the electrolyzer	4,78	9,05	17,76	21,49	23,94	24,75	25,27	20,88	18,49	13,06	8,04	5,31	[kWh/d]
Total recovered TE	13,83	26,20	51,42	62,22	66,95	67,77	68,29	60,45	53,52	37,80	23,27	15,38	[kWh/d]
Overall efficiency	**49,60**	**54,20**	**66,86**	**75,23**	**78,24**	**78,07**	**74,68**	**66,20**	**65,16**	**62,00**	**57,04**	**51,53**	[%]
Overall self-sufficiency	**50,70**	**56,45**	**72,98**	**84,62**	**87,47**	**86,30**	**81,13**	**72,46**	**70,87**	**66,26**	**59,59**	**52,90**	[%]

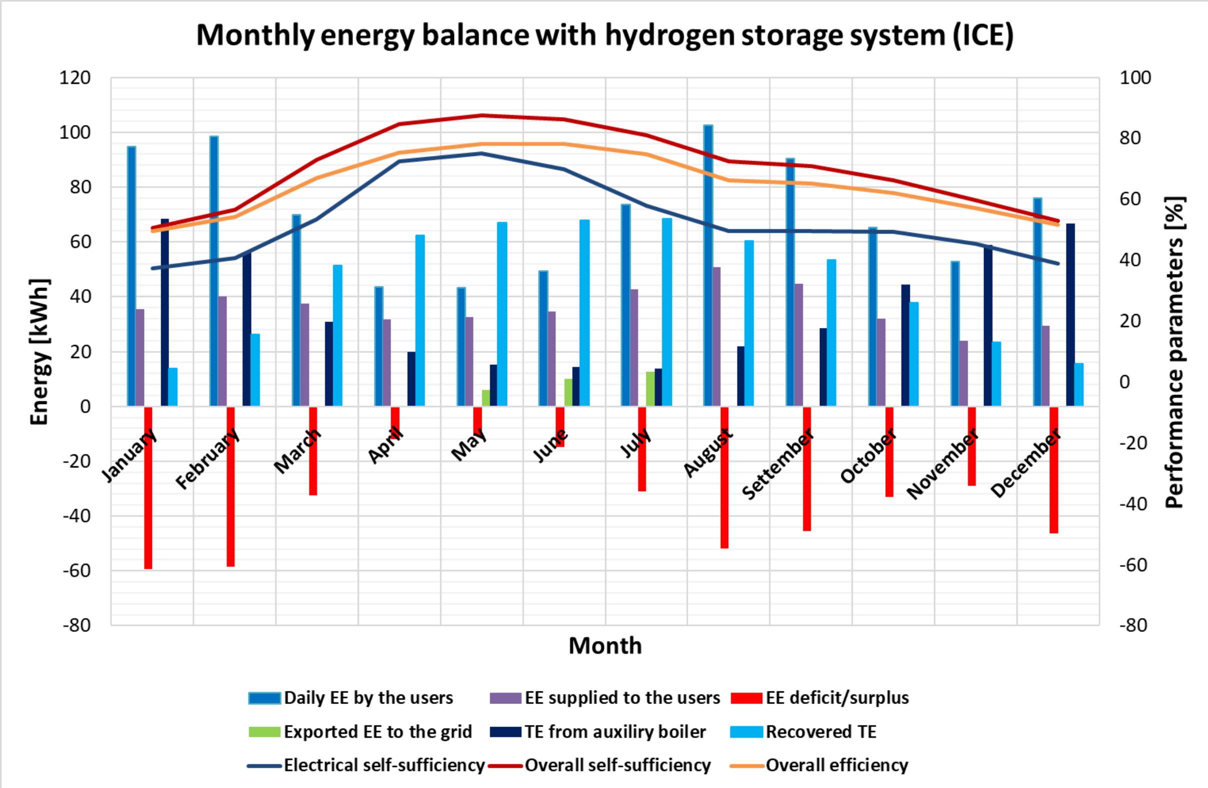

Figure 6.11. Monthly energy balance of 30 kWp of PV plant with hydrogen storage system installed in Milan.

Also for the system-ICE the trend is confirmed. However, due to the lower value of the electrical efficiency and therefore the higher EE losses during the storage, the energy always needs to be imported from the grid. This means that in this case, all the produced hydrogen during the day is consumed during the night, without the possibility of seasonal storage. Moreover, the hydrogen storage system with ICE shows the lowest electrical performance parameters with respect to the other technologies. Then, by averaging:

- The EE supplied to the users (E_{s-u}) results to be equal to 36,27 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 53,28%.
- The EE exchanged with the grid (E_g) in this case is equal to around 35,39 kWh_e/d of energy to be imported from the grid ($E_{i,g}$), and 2,40 kWh_e/d of energy to exported to the grid ($E_{e,g}$).

Also in this case, the higher EE production from the PV plant allows both a higher energy consumption from the electrolyser and a higher energy production from the ICE. This corresponds on average to a greater TE that can be recovered, thus decreasing that required from the auxiliary boiler. Moreover, due to the higher thermal efficiency, the recovered waste heat is greater than in the case with the FC, significantly reducing the energy required from the auxiliary boiler.

Thus, despite the lower electrical efficiency of the system in general present higher values with respect to the plant with the battery, especially from April to July. However, also in this case, the plant with the FC always presents the best overall performance parameters of the system,

- The overall self-sufficiency (SS_{oa}) is equal to around 70,14%.
- The overall efficiency (η_{oa}) is equal to around 64,90%.

6.2.2. Analysis of 40 kW_p PV plant with storage system: Milan

A further increasing to 40 kW_p of PV plant installed in Milan is now analyzed. The average monthly produced EE per day from the PV plant, the consumed one per day by the families and their difference for this case are reported in Figure 6.12.

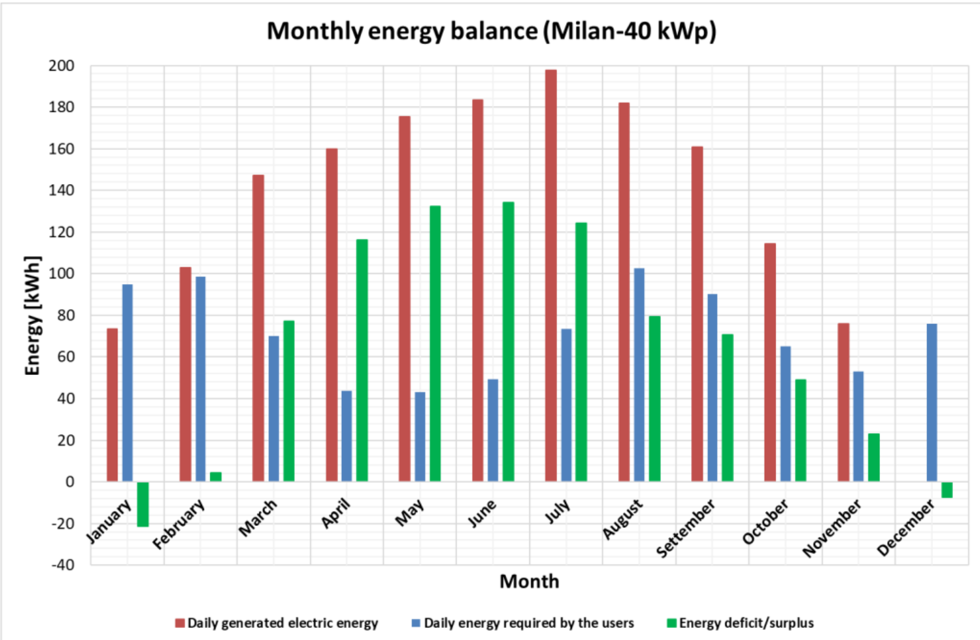

Figure 6.12. Produced EE, consumed one and their differences for 40 kWp of PV plant installed in Milan.

From this figure is possible to see that the plant could be almost independent by the grid.

In the case of the battery, having a size be equal to 161,52 kWh_e (S_b) (Page 64), the maximum storage capability is equal to 113,06 kWhe/d ($E_{ss,max}$) and the outcoming EE net of losses ($E_{ss,out}$) is equal to 96,97 kWh_e/d. Again, for thermal energy it is supplied by both the SWH system and the boiler system.

On the base of the given data, all the monthly energy flows are calculated, reported in the Table 6.7. and showed in the Figure 6.13.

Table 6.7. Monthly energy balance of 40 kWp of PV plant with battery installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	40,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	73,35	102,91	147,10	159,76	175,54	183,59	197,74	181,95	160,87	114,22	76,00	68,39	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Battery size	161,52												[kWh]
EE balance													
Storable EE during the day	41,74	70,06	123,76	145,20	161,13	167,14	173,23	147,75	130,76	92,50	58,37	43,12	[kWh/d]
Real storable EE during the day	23,40	44,33	113,06	113,06	113,06	113,06	113,06	113,06	113,06	63,94	39,37	26,02	[kWh/d]
Stored EE (Round-trip efficiency)	37,57	63,05	101,76	101,76	101,76	101,76	101,76	101,76	101,76	83,25	52,53	38,81	[kWh/d]
Output of EE (Self-discharge)	35,69	59,90	96,67	96,67	96,67	96,67	96,67	96,67	96,67	79,09	49,90	36,87	[kWh/d]
EE deficit/surplus	-27,54	-5,82	50,00	67,56	67,85	63,78	47,64	28,28	36,45	35,65	14,63	-13,67	[kWh/d]
Exported EE to the grid	0,00	0,00	10,70	32,14	48,06	54,08	60,16	34,69	17,69	0,00	0,00	0,00	[kWh/d]
EE supplied to the users	67,30	92,76	120,00	111,22	111,08	113,11	121,18	130,86	126,78	100,81	67,54	62,13	[kWh/d]
Electrical self-Sufficiency	**70,96**	**94,10**	**171,43**	**254,71**	**256,97**	**229,28**	**164,77**	**127,57**	**140,35**	**154,70**	**127,66**	**81,97**	[kWh/d]
TE balance													
TE from the auxiliary boiler	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Overall efficiency	**56,35**	**64,06**	**68,35**	**69,59**	**71,00**	**71,67**	**72,78**	**71,53**	**69,69**	**65,68**	**62,29**	**58,56**	[%]
Overall self-sufficiency	**57,67**	**66,53**	**86,27**	**92,97**	**93,09**	**91,38**	**85,48**	**79,81**	**82,04**	**79,72**	**68,91**	**60,09**	[%]

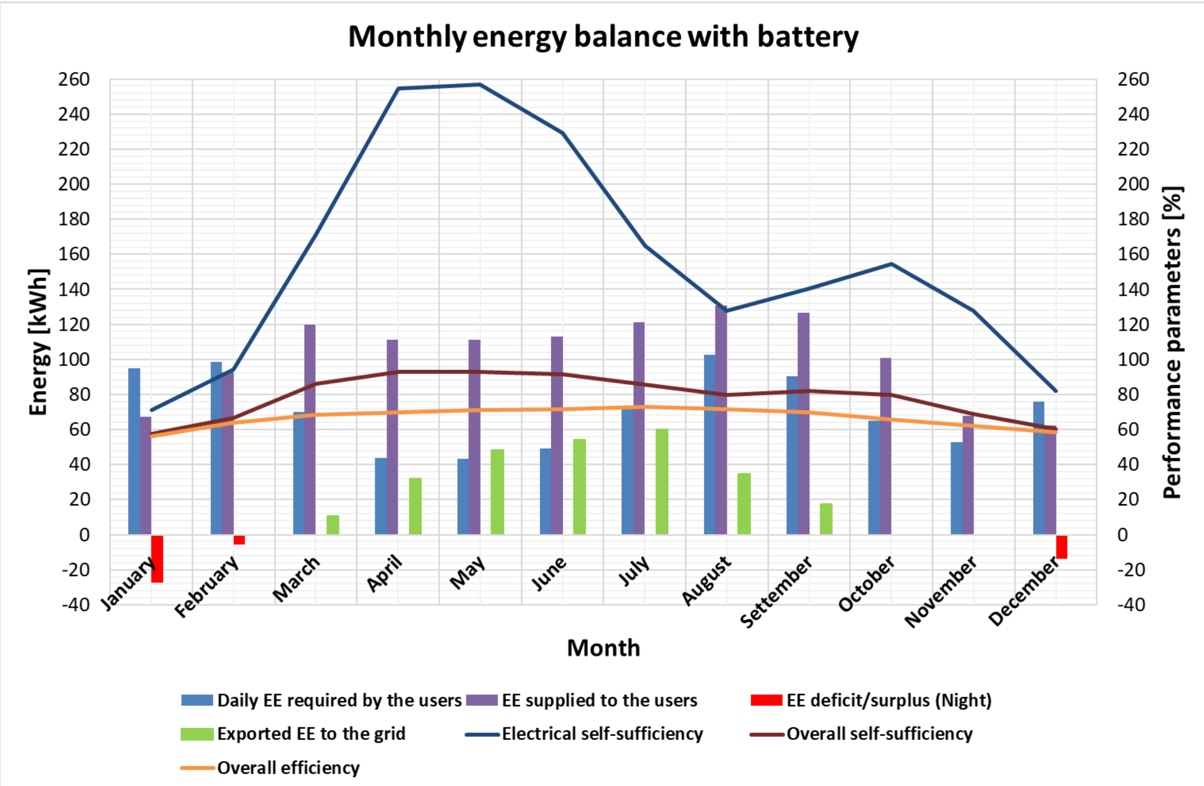

Figure 6.13. Monthly energy balance of 40 kWp of PV plant with battery installed in Milan.

As expected, thanks to the greater PV EE production, a higher stored energy (E_s) is reached. In this way, the output EE net of battery losses ($E_{ss,out}$) is almost able to satisfy the EE demand during the night, also during the autumn/winter period. Indeed, a low amount of EE is imported from the grid to fully meet the demand during this period. Thus, it is possible to say that the plant is almost independent from the grid. Indeed, in general, the EE supplied to the users and consequently the electrical self-sufficiency present on average even higher values. This last parameter is higher than 100% nine months over twelve, reaching very high peak during the spring/summer. Always during this period, the PV plant energy production is higher than the maximum storable energy, thus a certain amount of energy has to be exported to the grid, reaching values higher than in the previous cases. The averaged values of the main performance parameters result in:

- The EE supplied to the users (E_{s-u}) results to be equal to 102,1 kWh_e/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 156,21%.
- The EE exchanged with the grid (E_g) in this case is equal to 3,92 kWh_e/d from imported from the grid ($E_{i,g}$) and 21,46 kWh_e/d to be exported to the grid ($E_{e,g}$).

Also the overall performance parameters present the same trend obtained in the previous paragraph:

- The overall self-sufficiency (SS_{oa}) is equal to around 78,66%.
- The overall efficiency (η_{oa}) is equal to around 66,80%.

Applying the monthly energy balance in the case of hydrogen storage system with the fuel cell, the electrolyzer size is equal to 36 kW_e, thus with a maximum EE consumption of 166,75 kWh_e/d ($E_{ss,max}$) (Page 65). Instead, the metal hydrides tank is always considered with a geometrical volume equal to 750 l, therefore with a maximum hydrogen storage capability of 27,72 kg_{H2}. While the fuel cell size equal to 5,8 kW_e, with a maximum output of EE equal to 52,04 kWh_e/d. While, as said in the previous case is always valid concerning the thermal energy balance.

The results are reported in the Table 6.8. and plotted in the Figure 6.14.

Table 6.8. Monthly energy balance of 40 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	40,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	73,35	102,91	147,10	159,76	175,54	183,59	197,74	181,95	160,87	114,22	76,00	68,39	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	36,00												[kW]
MH size (Geometrical volume)	750,00												[l]
Fuel cell size	5,80												[kW]
EE balance													
Storable EE during the day	41,74	70,06	123,76	145,20	161,13	167,14	173,23	147,75	130,76	92,50	58,37	43,12	[kWh/d]
Real storable EE during the day	41,74	70,06	123,76	145,20	161,13	166,75	166,75	147,75	130,76	92,50	58,37	43,12	[kWh/d]
Mass of produced hydrogen	0,78	1,31	2,32	2,72	3,02	3,12	3,12	2,77	2,45	1,73	1,09	0,81	[kWh/d]
Energy stored via hydrogen	26,05	43,72	77,24	90,62	100,56	104,07	104,07	92,21	81,61	57,73	36,43	26,91	[kWh/d]
Output of EE	13,03	21,86	38,62	45,31	50,28	52,04	52,04	46,11	40,80	28,86	18,21	13,46	[kWh/d]
EE deficit/surplus	-50,20	-43,85	-8,05	16,20	21,46	19,15	3,00	-22,28	-19,42	-14,58	-17,06	-37,08	[kWh/d]
Exported EE to the grid	0	0	0	0,80	21,46	19,54	9,48	0	0	0	0	0	[kWh/d]
Theoretical def./exc. of H_2 (daily)	-3,01	-2,63	-0,48	0,97	1,29	1,15	0,18	-1,34	-1,17	-0,87	-1,02	-2,23	[kg]
Theoretical def./exc. of H_2 (monthly)	-93,38	-73,68	-14,97	29,16	39,92	34,47	5,59	-41,44	-34,96	-27,11	-30,70	-68,98	[kg]
Cumalated of H_2	0	0	0	27,72	27,72	27,72	27,72	0	0	0	0	0	[kg]
Real excess of H_2 per month	0	0	0	27,72	0	0	0	0	0	0	0	0	[kg]
Real excess of H_2 per day	0	0	0	0,92	0	0	0	0	0	0	0	0	[kg]
Real energy surplus	0	0	0	15,40	0	0	0	0	0	0	0	0	[kWh/d]
EE supplied to the users	44,64	54,72	61,95	59,07	43,23	49,33	73,55	80,30	70,91	50,58	35,85	38,72	[kWh/d]
Electrical self-sufficiency	**47,07**	**55,51**	**88,51**	**135,26**	**100,00**	**100,00**	**100,00**	**78,28**	**78,50**	**77,63**	**67,76**	**51,08**	[kWh/d]
TE balance													
TE from the auxiliary boiler	60,64	46,03	18,30	8,01	19,76	2,01	0,00	5,92	14,69	34,44	52,06	59,93	[kWh/d]
Recovered TE from the FC	13,03	21,86	38,62	45,06	43,58	46,06	46,82	46,11	40,80	28,86	18,21	13,46	[kWh/d]
Recovered TE from the electrolyzer	8,52	14,30	25,27	29,12	18,85	34,12	35,37	30,17	26,70	18,89	11,92	8,80	[kWh/d]
Total recovered TE	21,55	36,16	63,89	74,18	62,44	80,19	86,46	76,27	67,50	47,75	30,13	22,26	[kWh/d]
Overall efficiency	**55,70**	**62,94**	**81,38**	**86,51**	**75,43**	**86,36**	**91,30**	**81,67**	**79,59**	**73,56**	**65,18**	**57,83**	[%]
Overall self-sufficiency	**57,24**	**65,82**	**88,76**	**103,55**	**90,48**	**99,06**	**101,80**	**89,44**	**86,61**	**78,65**	**68,19**	**59,61**	[%]

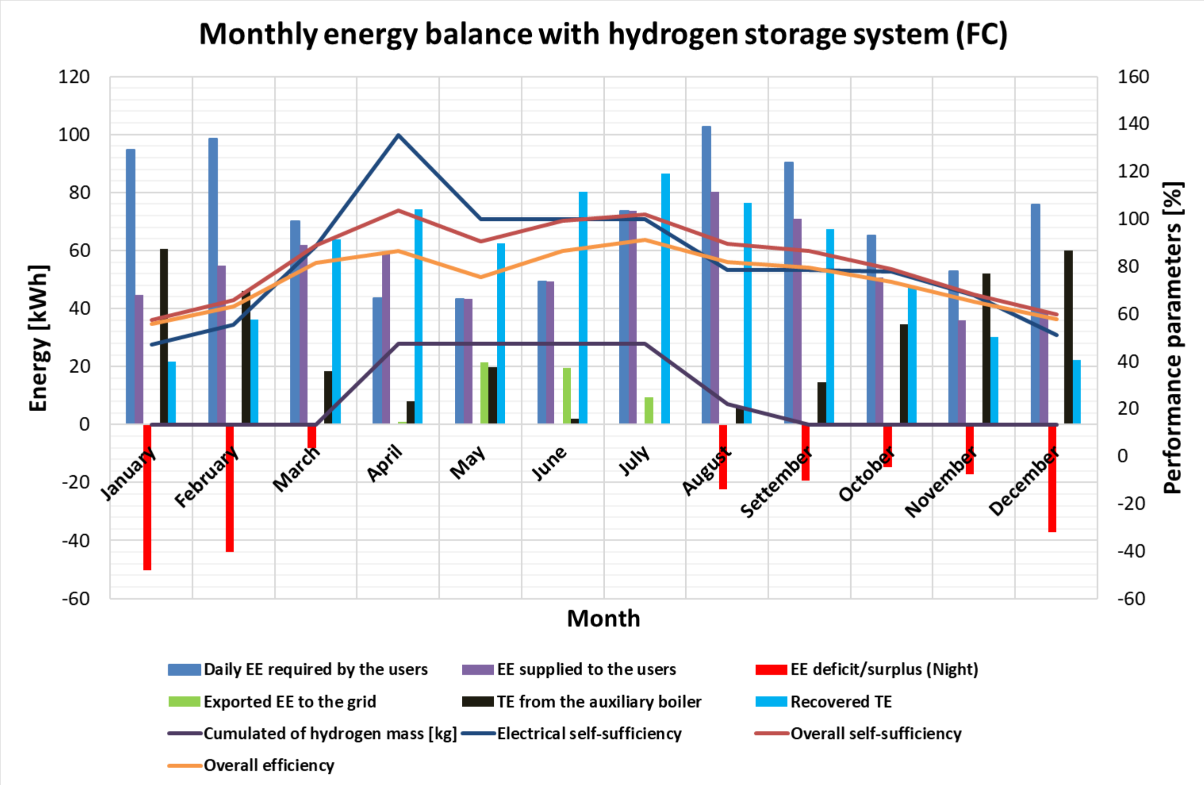

Figure 6.14. Monthly energy balance of 40 kWp of PV plant with hydrogen storage system installed in Milan.

As can be seen, the trend of the monthly EE balance is quite different of that of the previous paragraph, for the same system, especially from April to July. However, also in this case, due to the higher installed PV power and consequently the higher produced EE, the energy supplied to the users and the electrical self-sufficiency show on average higher values, while the energy imported from the grid shows lower ones. Moreover, due to this higher EE production from the PV plant, from April to July, the output of energy from the storage system is higher than the energy required during the night. This means that the exceeding hydrogen mass can be cumulated to be used to compensate the energy that should be imported during the night from the grid. In this case, 27,72 kg_{H2} of hydrogen are stored corresponding to 923,9 kWh_{ch} of chemical energy to be used in the following months, producing an increasing of both the EE supplied to the end users and the electrical self-sufficiency. However, the metal hydrides tank is already saturated in April and, also in this case, the hydrogen is considered to be consumed in the same production month. For this reason, the electrical self-sufficiency shows a peak that is higher than 100%, although in the realty the hydrogen could be consumed in the autumn/winter period. Instead, from May to July, the exceeding amount of EE cannot be used to produce hydrogen, because of the saturation of the storage system. Thus, this has to be exported to the grid. To this purpose, the EE supplied to the users is equal to the required one, thus the electrical self-sufficiency shows a flat line that is equal to 100%. Resuming, the averaged values of the main electrical performance parameters are obtained, thus:

- The EE supplied to the users (E_{s-u}) results to be equal to 55,24 kWh_e/d.

- The electrical self-sufficiency (SS) of the system results to be equals to 81,63%.
- The EE exchanged with the grid (E_g) in this case is equal to around 17,71 kWh_e/d of energy to be imported from the grid ($E_{i,g}$), and 4,27 kWh_e/d of energy to exported to the grid ($E_{e,g}$).

As concern the TE balance, the higher electrical energy production from the PV plant allows both a higher EE consumption from the electrolyser and a higher EE production from the fuel cell. This corresponds on average to a greater TE that can be recovered, thus decreasing that required from the auxiliary boiler.

Thus, the overall performance parameters show almost identical trend with respect to the others cases, although in general they present higher values. However, from May to July, the exported energy to the grid represents a certain amount of losses thermal energy, because the elctrolyzer and, as a consequence, the fuel cell loss a part of the working functioning. This phenomenon generates a decreasing of the overall performance parameters during these months.

Instead, as concern the overall performance parameters and always considering the medium of the monthly values, the following results are obtained:

- The overall self-sufficiency (SS_{oa}) is equal to around 82,43%.
- The overall efficiency (η_{oa}) is equal to around 74,79%.

At the end, the monthly energy balance is applied in the case of the hydrogen storage system with ICE. Here, both the electrolyzer size and the metal hydrides tanks size are the same of the previous energy analysis, while the ICE size is equal to 3 kW_e, because of it has to be able to produce a maximum EE equal to 27,06 kWh_e/d (Page 66). Instead, always the same considerations are applied considering the thermal energy balance. The results are showed in the Table 6.9. and in the Figure 6.15.

Table 6.9. Monthly energy balance of 40 kWp of PV plant with hydrogen storage system installed in Milan.

	Milan												
Average energy requirements	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Set**	**Oct**	**Nov**	**Dec**	
Average EE consumption	94,84	98,57	70,00	43,67	43,23	49,33	73,55	102,58	90,33	65,16	52,90	75,81	[kWh/d]
Average EE consumption (day)	31,61	32,86	23,33	14,56	14,41	16,44	24,52	34,19	30,11	21,72	17,63	25,27	[kWh/d]
Average EE consumption (night)	63,23	65,71	46,67	29,11	28,82	32,89	49,03	68,39	60,22	43,44	35,27	50,54	[kWh/d]
Avergare TE consumption	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	164,38	[kWh/d]
Renewable technologies													
Installed PV power	40,00												[kWp]
Collector area	40,00												[m^2]
Storage tank volume	2000,00												[l]
Average renewable energy													
Average produced EE from the PV	73,35	102,91	147,10	159,76	175,54	183,59	197,74	181,95	160,87	114,22	76,00	68,39	[kWh/d]
Average produced TE from the SWH	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	82,19	[kWh/d]
Design of the storage system													
Electrolyzer size	36,00												[kW]
MH size (Geometrical volume)	750,00												[l]
ICE size	3,00												[kW]
EE balance													
Storable EE during the day	41,74	70,06	123,76	145,20	161,13	167,14	173,23	147,75	130,76	92,50	58,37	43,12	[kWh/d]
Real storable EE during the day	41,74	70,06	123,76	145,20	161,13	166,75	166,75	147,75	130,76	92,50	58,37	43,12	[kWh/d]
Mass of produced hydrogen	0,78	1,31	2,32	2,72	3,02	3,12	3,12	2,77	2,45	1,73	1,09	0,81	[kWh/d]
Energy stored via hydrogen	26,05	43,72	77,24	90,62	100,56	104,07	104,07	92,21	81,61	57,73	36,43	26,91	[kWh/d]
Output of EE	6,77	11,37	20,08	23,56	26,15	27,06	27,06	23,98	21,22	15,01	9,47	7,00	[kWh/d]
EE deficit/surplus	-56,45	-54,35	-26,58	-5,55	-2,67	-5,83	-21,97	-44,41	-39,00	-28,43	-25,80	-43,54	[kWh/d]
Exported EE to the grid	0	0	0	0	0	0,39	6,47	0	0	0	0	0	[kWh/d]
Theoretical def./exc. of H_2 (daily)	-6,51	-6,27	-3,07	-0,64	-0,31	-0,67	-2,54	-5,12	-4,50	-3,28	-2,98	-5,02	[kg]
Theoretical def./exc. of H_2 (monthly)	-201,95	#####	-95,10	-19,21	-9,56	-20,19	-78,61	-158,9	#####	######	-89,31	#####	[kg]
Cumalated of H_2	0	0	0	0	0	0	0	0	0	0	0	0	[kg]
Real excess of H_2 per month	0	0	0	0	0	0	0	0	0	0	0	0	[kg]
Real excess of H_2 per day	0	0	0	0	0	0	0	0	0	0	0	0	[kg]
Real energy surplus	0	0	0	0	0	0	0	0	0	0	0	0	[kWh/d]
EE supplied to the users	38,39	44,23	43,42	38,12	40,55	43,50	51,57	58,17	51,33	36,73	27,11	32,27	[kWh/d]
Electrical self-Sufficiency	**40,48**	**44,87**	**62,02**	**87,29**	**93,82**	**88,18**	**70,12**	**56,71**	**56,82**	**56,37**	**51,24**	**42,56**	[kWh/d]
TE balance													
TE from the auxiliary boiler	57,52	40,78	9,03	0,00	0,00	0,00	0,00	0,00	4,90	27,51	47,69	56,70	[kWh/d]
Recovered TE from the ICE	16,15	27,11	47,89	56,19	62,35	64,52	64,52	57,17	50,60	35,79	22,58	16,68	
Recovered TE from the electrolyzer	8,52	14,30	25,27	29,65	32,90	34,12	35,37	30,17	26,70	18,89	11,92	8,80	[kWh/d]
Total recovered TE	24,67	41,41	73,16	85,83	95,24	98,65	99,89	87,34	77,29	54,68	34,50	25,49	[kWh/d]
Overall efficiency	**53,89**	**59,89**	**75,03**	**83,29**	**83,71**	**82,74**	**79,54**	**73,80**	**73,46**	**68,79**	**62,07**	**55,79**	[%]
Overall self-sufficiency	**56,03**	**63,82**	**84,80**	**99,08**	**105,00**	**104,97**	**98,20**	**85,29**	**82,76**	**75,63**	**66,18**	**58,26**	[%]

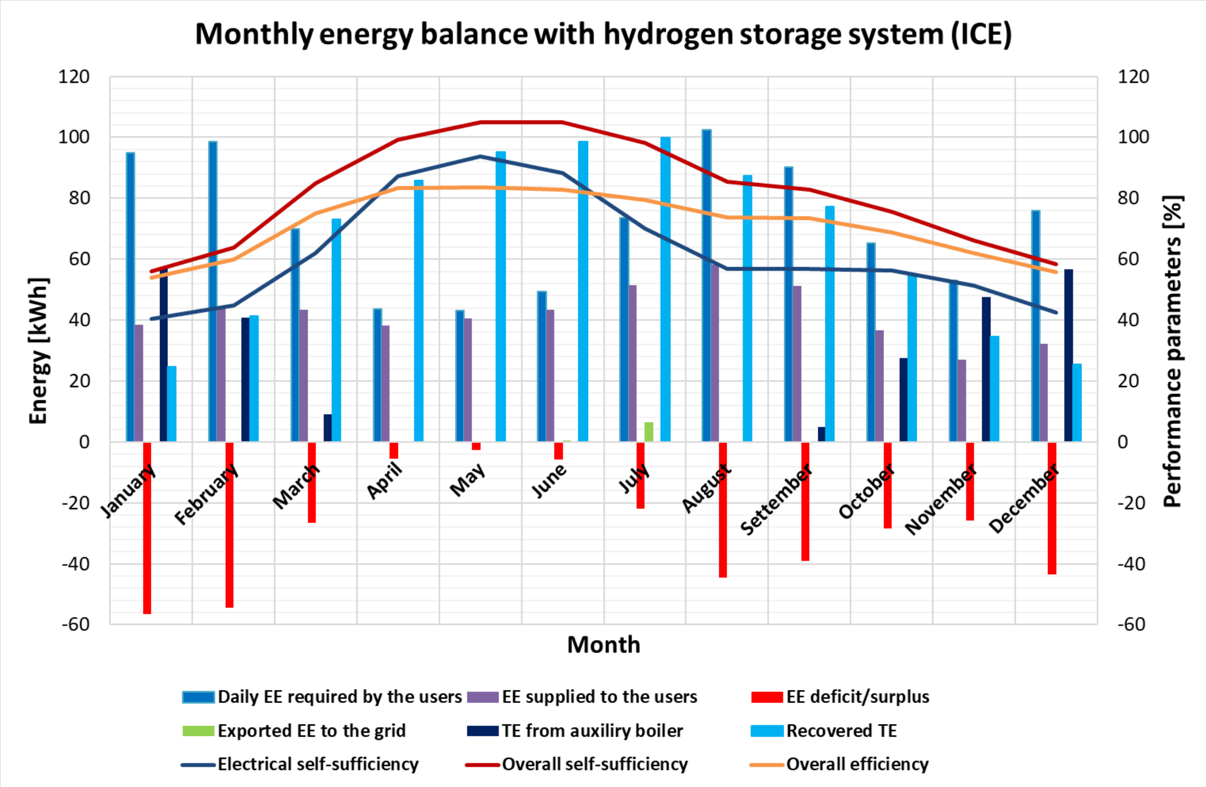

Figure 6.15. Monthly energy balance of 40 kWp of PV plant with hydrogen storage system installed in Milan.

So that, the averaged values are:

- The EE supplied to the users ($E_{s\text{-}u}$) results to be equal to 42,11 kWh$_e$/d.
- The electrical self-sufficiency (SS) of the system results to be equals to 62,54%.
- The EE exchanged with the grid (E_g) in this case is equal to around 29,55 kWh$_e$/d of energy to be imported from the grid ($E_{i,g}$), and 0,57 kWh$_e$/d of energy to exported to the grid ($E_{e,g}$).

Also in this case, the higher electrical energy production by the PV plant allows both a higher EE consumption from the electrolyser and a higher EE production from the ICE. This corresponds on average to a greater TE that can be recovered, thus decreasing that required by the auxiliary boiler. Further, in some months, the TE needed by the auxiliary boiler is equal to zero. Moreover, due to the higher thermal efficiency, the recovered waste heat is greater than in the case with the FC, significantly reducing the energy required from the auxiliary boiler.

Thus, despite the lower electrical efficiency of the system, the overall performance parameters in general present higher values with respect to the plant with the battery. However, also in this case, the plant with the FC always presents the best overall performance parameters of the system, although it presents worse characteristics from April to July. Instead, as concern the average values of the overall performance parameters the following results are obtained:

- The overall self-sufficiency (SS_{oa}) is equal to around 81,67%
- The overall efficiency (η_{oa}) is equal to around 71%.

6.2.3. Graphical visualizations and comments of the results: Milan

In the previous paragraphs, the performance parameters on monthly base in the case of the PV plant with the different storage systems installed in Milan have been obtained..The averaged results are reported in table 6.10.

Table 6.10. Summary of the obtained results by the energy balance on annual and monthly base.

	Milan									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Installed PV power	20	30	40	20	30	40	20	30	40	[kW_p]
Energy balance on annual base										
Electrical self-sufficiency	89,27	132,23	175,2	52,73	67,62	82,52	43,36	51,21	58,95	[%]
Overall efficiency	60,78	66,28	68,97	58,67	68,65	78,17	56,53	64,76	72,46	[%]
Overall self-sufficiency	61,93	74,98	88,03	60,57	72,59	84,6	59,16	70,09	81,01	[%]
Energy balance on monthly base										
Electrical self-sufficiency	79,04	117,62	156,2	55,21	71,7	81,63	44,71	53,28	62,54	[%]
Overall efficiency	57,32	63,37	66,8	58,93	68,44	74,79	56,81	64,9	71	[%]
Overall self-sufficiency	57,37	68,02	78,66	60,58	72,62	82,43	59,19	70,14	81,67	[%]
Differences										
Electrical self-sufficiency	-10,23	-14,61	-19,00	2,48	4,08	-0,89	1,35	2,07	3,59	[%]
Overall efficiency	-3,46	-2,91	-2,17	0,26	-0,21	-3,38	0,28	0,14	-1,46	[%]
Overall self-sufficiency	-4,56	-6,96	-9,37	0,01	0,03	-2,17	0,03	0,05	0,66	[%]

In this table are also reported the results obtained in the chapter 5 and the differences between the two balances. In this way, it is possible to see that the energy balance on annual base does not show a high level of accuracy of the results. This is especially highlighted in the case of battery. Indeed, the performance parameters present a huge decrease from the energy balance on annual base to that on monthly base. Further, this gap increases with the increasing of the PV power, both in the case of the self-sufficiency and the overall one. This is mainly due to the fact that the battery it is not able to recover heat and have limitations in storage capability during spring/summer time. While as concern the hydrogen storage system, the results show in some cases an increase of the values in the monthly energy balance in respect to the annual average. This because hydrogen storage-based system is more flexible in following up the seasonal variations, although its electrical self-sufficiency is lower than that of batteries.

For a better vision, the main performance parameters obtained by the energy balance on monthly base are represented in the Figure 6.16, Figure 6.17. and Figure 6.18, that allow also a comparison of the obtained results to those obtained in the previous chapter.

The electrical self-sufficiency is represented in the Figure 6.16. From this figure it is possible to see that the trend of the electric self-sufficiency as a function of the installed PV power is always the same compared to that of the Figure 5.13 (Page 68). In particular, as concern the battery, it shows both lower values and a lower slope. Instead, as concern the hydrogen storage systems, it shows both slightly higher values and a greater slope. However, the battery always shows higher values with respect the hydrogen storage systems.

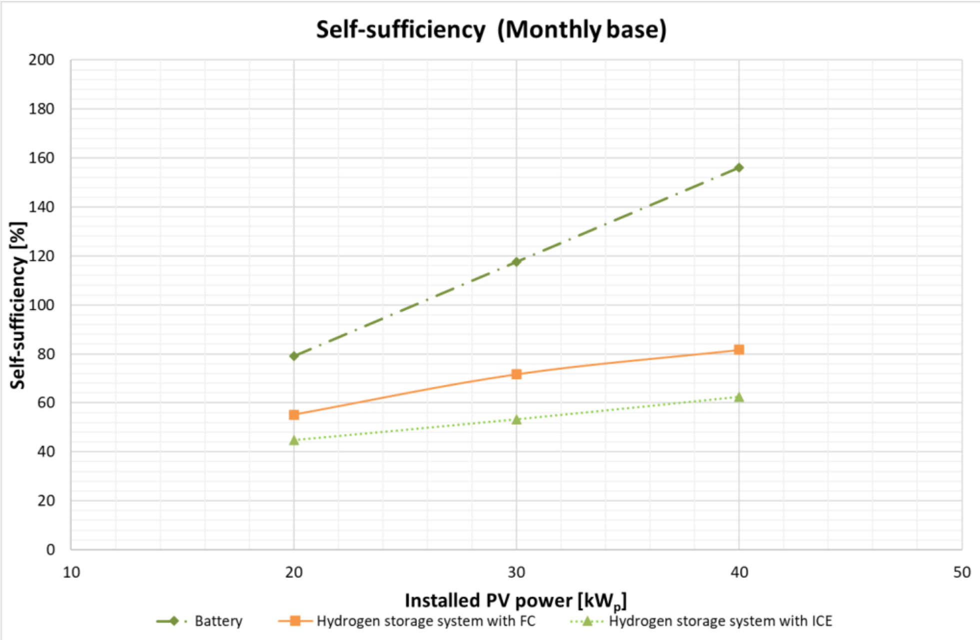

Figure 6.16. Electrical self-sufficiency of the system located in Milan.

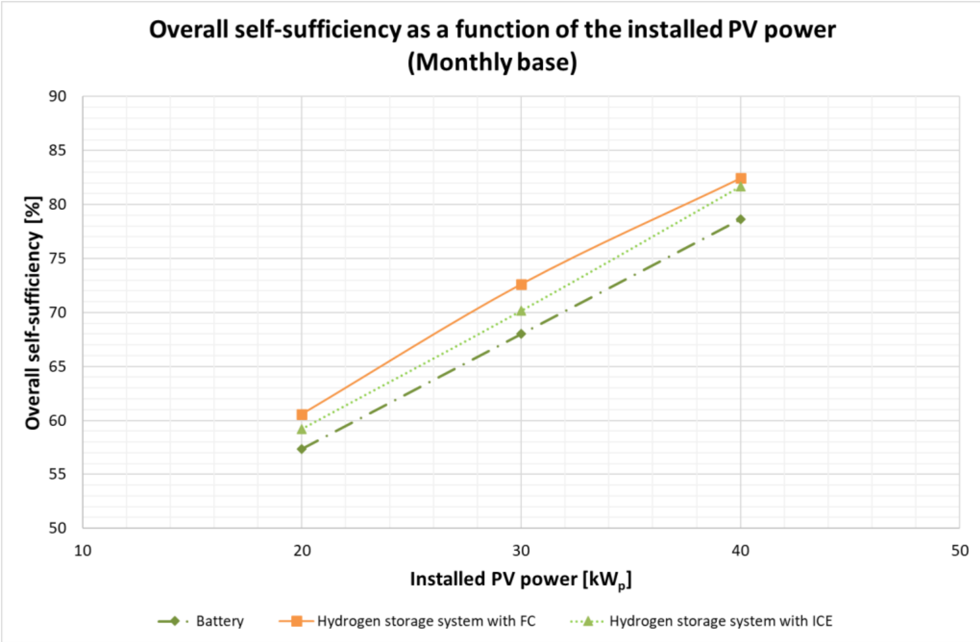

Figure 6.17. Overall self-sufficiency of the system located in Milan.

Also for the overall self-sufficiency the trend is always the same compared to that in the Figure 5.14. (Page 69). However, in this case the hydrogen storage systems present higher values with respect to the battery.

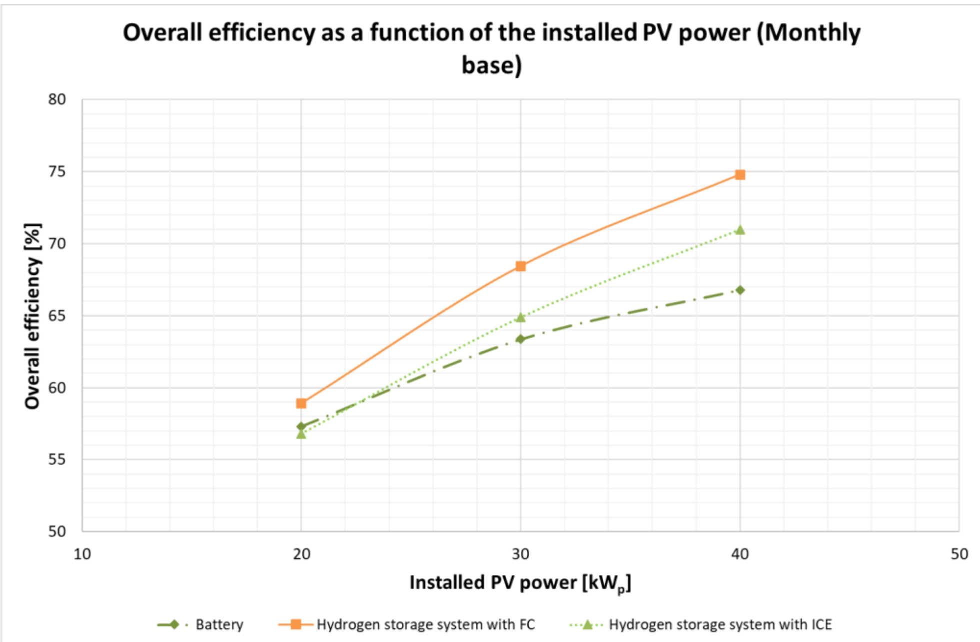

Figure 6.18. Overall efficiency of the system located in Milan.

As concern the overall efficiency, the trend is always the same of that reported in the Figure 5.15. (Page 70). However, the battery presents lower values. Thus, the hydrogen storage system with FC always presents values higher than the battery. Instead, as concern the hydrogen storage system with

ICE, it already presents values higher than the battery just over 20kW$_p$ of PV power, while this happens over 30kW$_p$ of PV power in yearly average-based analysis.

6.3. Analysis of the PV plant with storage system: Rome

Once the only variable to take into account are the PV specific energy production and the percentage of covered thermal energy by the SWH system, moving from a location to another one, exactly the same procedure of the previous paragraphs is applied in the case of Rome, representing the Centre Italy region. However, in the case of battery, it is needed to remember that an exceeding amount of storable energy usable during the night ($E_{ss,r}$) is not really stored from June to August, due to the low probability of cloudy/raining days and related saturation of the storage system. Thus, this energy has to be exported to the grid, decreasing the energy supplied to the users and the electrical self-sufficiency of the system. Consequently, also the overall self-sufficiency decreases, while this exported energy is a gain to the overall system efficiency.

For brevity the montly resultas are not reported and we go directly to the averaged results. In analogy with Milan case, the results are summarised in the Table 6.11. Moreover, the main performance parameters are plotted in the Figure 6.19., Figure 6.20. and Figure 6.21. In this way, it is easier to make a comparison between the different applied storage systems at the different installed PV powers in Rome, also making a comparison with the case of Milan.

Table 6.11. Summary of the obtained results by the energy balance on annual and monthly base.

	Rome									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Installed PV power	20	30	40	20	30	40	20	30	40	[kW$_p$]
Energy balance on annual base										
Electrical self-sufficiency	103,07	152,93	202,81	57,52	74,8	92,11	45,91	54,9	63,9	[%]
Overall efficiency	67,93	70,56	72,95	65,28	76,55	87,23	62,52	71,86	78,62	[%]
Overall self-sufficiency	69,6	84,75	99,9	67,92	81,86	95,8	66,15	78,94	91,66	[%]
Energy balance on monthly base										
Electrical self-sufficiency	93,95	130,71	165,61	60,8	78,63	88,95	47,64	57,98	68	[%]
Overall efficiency	63,73	68,76	71,54	65,61	75,72	82,45	66,43	71,71	76,45	[%]
Overall self-sufficiency	65,22	75,45	84,95	68,2	81,37	90,31	62,83	79,53	92,36	[%]
Differences										
Electrical self-sufficiency	-9,12	-22,22	-37,20	3,28	3,83	-3,16	1,73	3,08	4,10	[%]
Overall efficiency	-4,20	-1,80	-1,41	0,33	-0,83	-4,78	3,91	-0,15	-2,17	[%]
Overall self-sufficiency	-4,38	-9,30	-14,95	0,28	-0,49	-5,49	-3,32	0,59	0,70	[%]

The trend of the differences between the two balances is almost the same than in the case of Milan. However, in the case of battery, a stronger decreasing of the electrical self-sufficiency and the overall one is highlighted. This is mainly due to the energy surplus that has to be exported to the grid from June to August.

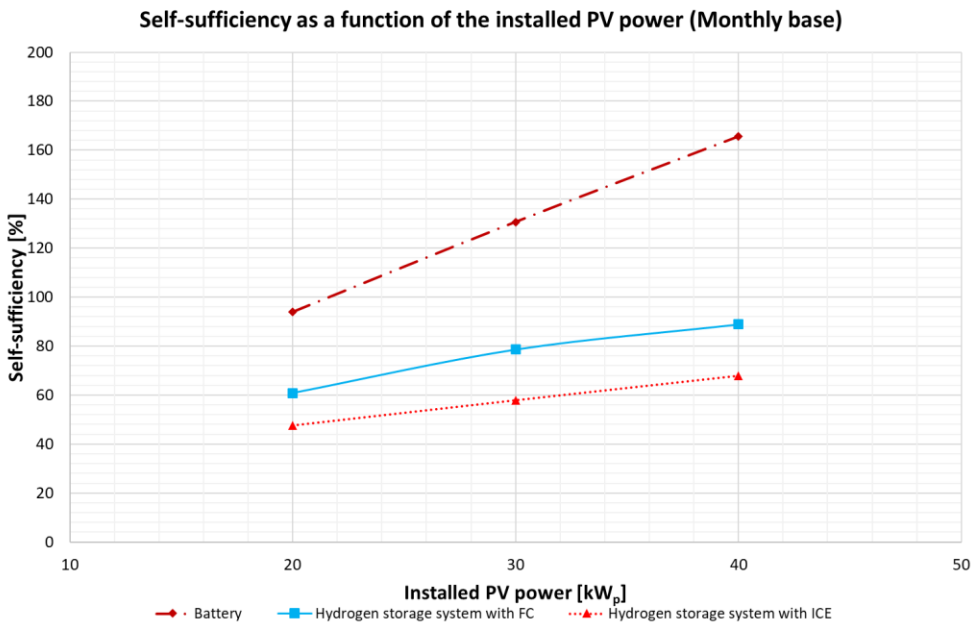

Figure 6.19. Electrical self-sufficiency of the system located in Rome.

From this figure it is possible to see that the trend of the electric self-sufficiency as a function of the installed PV power is always the same compared to that of the Figure 5.17. (Page 72). Although, the battery shows lower values while the hydrogen storage systems show both slightly higher values. However, the battery always shows higher values with respect the hydrogen storage systems.

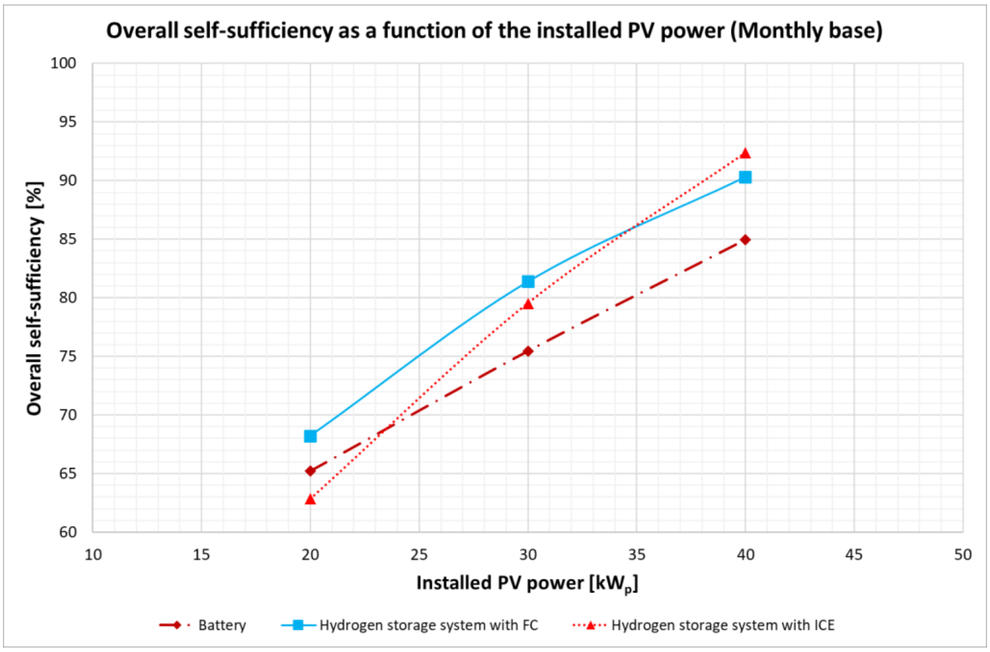

Figure 6.20. Overall self-sufficiency of the system located in Rome.

The trend of overall self-sufficiency is slightly different compared to that in the Figure 5.18. (Page 73) Indeed, the battery and the hydrogen storage systems with FC present lower values, while for the hydrogen storage system with ICE this is only valid at 20 kW_p of PV power. After it overcomes first batteries and then also the FC option. This could be attributed to the lower efficiency in electric energy production of ICE in respect to FC. In this way ICE burns more hydrogen for producing the same quantity of electricity reducing saturation events of the storage system and supplying more heat.

This analysis is confirmed by the overall efficiency behavior. The H-FC system is more efficient than H-ICE system when storage system saturation is present, because the exported energy to the grid acts positively on the overall efficiency of the system.

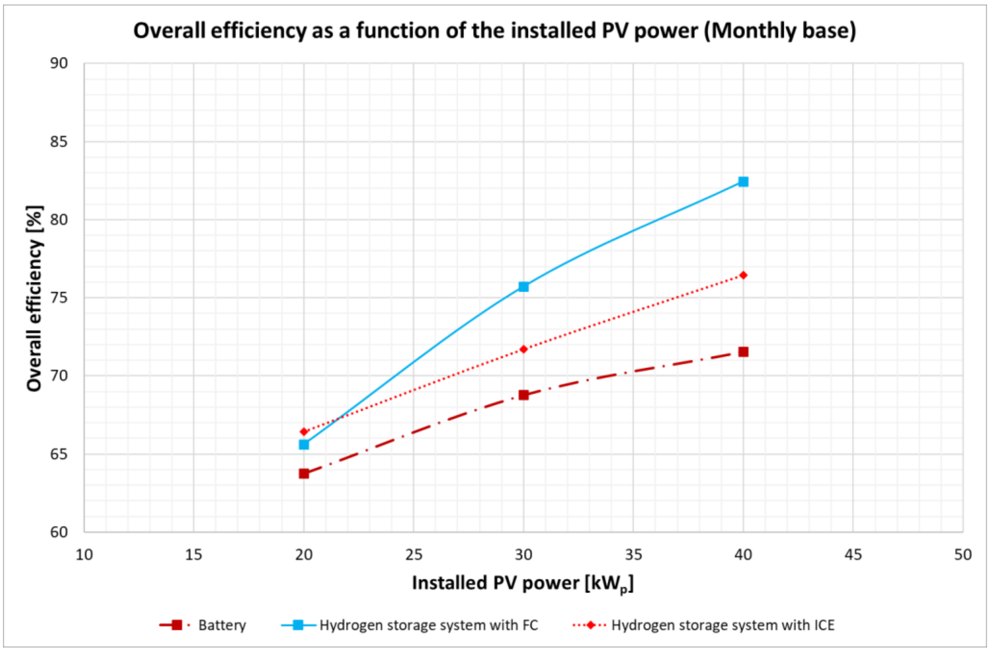

Figure 6.21. Overall efficiency of the system located in Rome.

6.4. Analysis of PV plant with storage system: Syracuse

The calculations have been repeated for the city of Syracuse, representing the South of Italy area. Results are summarized in the Table 6.12. and the main performance parameters are represented in the Figure 6.22., Figure 6.23. and Figure 6.24. Like in the case of the PV plant whit battery installed in Rome, it is needed to remember that an exceeding amount of storable energy is not really stored, because of the low probability of cloudy/raining days that generate the saturation of the storage system. However, this phenomenon has to be extended from May to October. Thus, a higher amount of energy has to be exported to the grid. So that, in respect to the yearly average calculation, the overall efficiency is increasing and the calculated self-sufficiency decreases. This is a clear demonstration that yearly average is not a good system for dimensioning this kind of residential poly-generation system and, probably more deep analyses are necessaries for a very good dimensioning. This aspect will be further considered in the next chapter.

Table 6.12. Summary of the obtained results by the energy balance on annual and monthly base.

	Syracuse									
	Battery			Hydrogen S.S. (FC)			Hydrogen S.S. (ICE)			
Installed PV power	20	30	40	20	30	40	20	30	40	[kW$_p$]
Energy balance on annual base										
Electrical self-sufficiency	110,66	164,34	218	60,14	78,75	97,36	47,23	56,95	66,63	[%]
Overall efficiency	71,22	73,97	76,01	70,37	82,28	90	67,34	77,01	79,49	[%]
Overall self-sufficiency	75,39	91,7	108	73,52	88,52	103,53	71,63	85,33	98,86	[%]
Energy balance on monthly base										
Electrical self-sufficiency	95,56	121,79	145,44	63,5	81,36	92,26	49,02	58,36	71,07	[%]
Overall efficiency	68,02	72,64	74,55	70,72	80,09	86,17	67,58	75,99	79	[%]
Overall self-sufficiency	69,66	77,08	83,69	73,77	87,74	96,73	71,82	84,68	99,81	[%]
Differences										
Electrical self-sufficiency	-15,10	-42,55	-72,56	3,36	2,61	-5,10	1,79	1,41	4,44	[%]
Overall efficiency	-3,20	-1,33	-1,46	0,35	-2,19	-3,83	0,24	-1,02	-0,49	[%]
Overall self-sufficiency	-5,73	-14,62	-24,31	0,25	-0,78	-6,80	0,19	-0,65	0,95	[%]

The trend of the differences between the two balances is almost the same than in the case of Milan and Rome. As expected, in the case of battery, a further decreasing of the self-sufficiency (electric and overall) is highlighted. This is mainly due to the energy surplus that has to be exported to the grid from May to October as consequence of the storage saturation.

Like in previous cases, the main obtained performance parameters by the energy balance on monthly base are plotted in the Figure 6.22., Figure 6.23. and Figure 6.24.

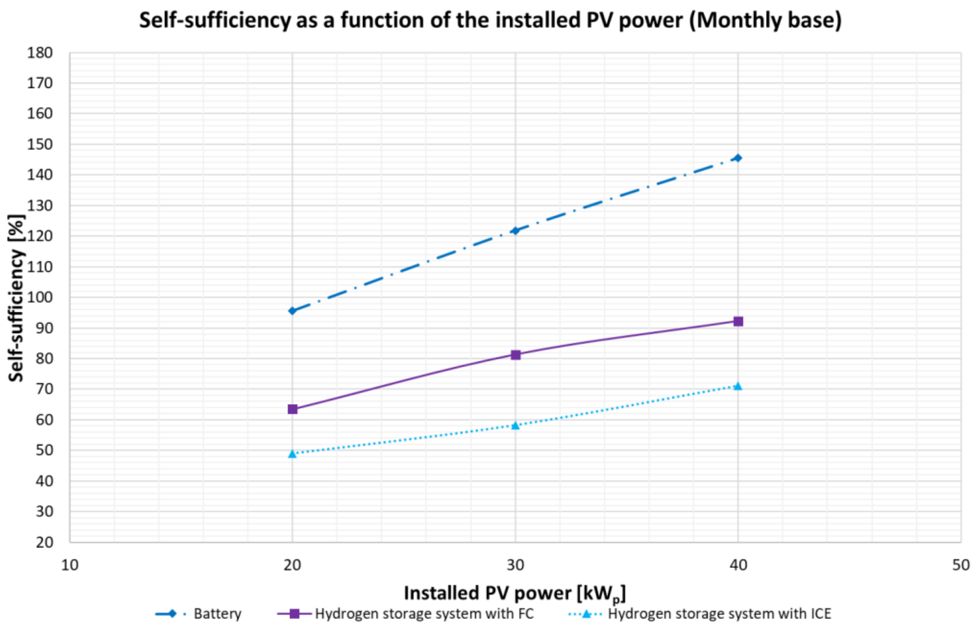

Figure 6.22. Electrical self-sufficiency of the system located in Syracuse.

It is possible to see that the trend of the electrical self-sufficiency as a function of the installed PV power is always the same compared to that of the Figure 5.21. (Page 75). Although, the battery shows lower values, while the hydrogen storage systems show slightly higher values. Thus, the gap between the two storage systems is strongly reduced. However, the battery always shows higher values.

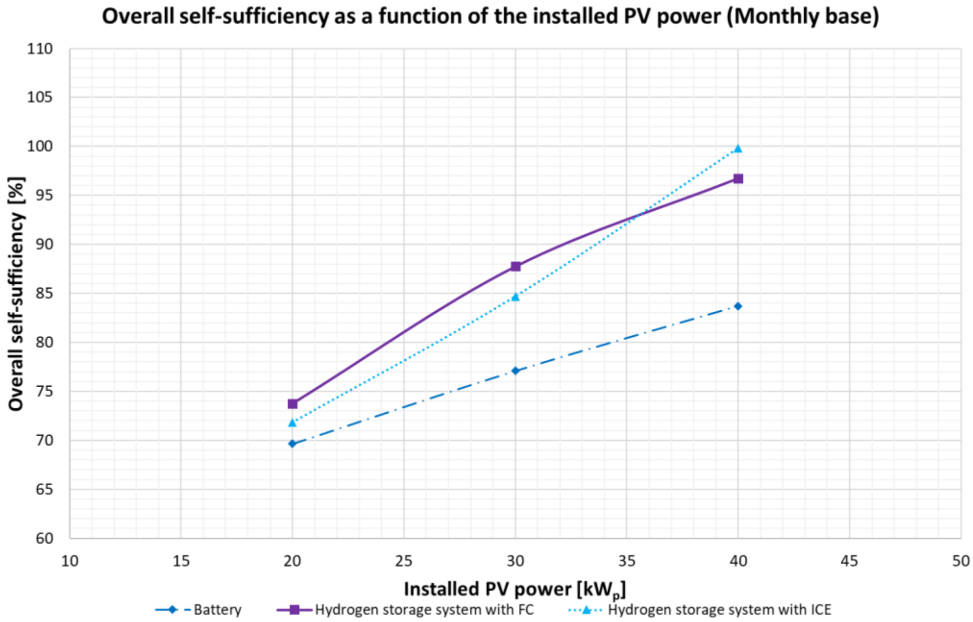

Figure 6.23. Overall self-sufficiency of the system located in Syracuse.

While for the overall self-sufficiency, the trend is slightly different compared to that in the Figure 5.22. (Page 76). Confirming, if necessary, the importance of the system resilience against storage saturation. Moreover, in Syracuse, both the hydrogen storage systems have a better performance than the battery also at the lowest considered PV plant power.

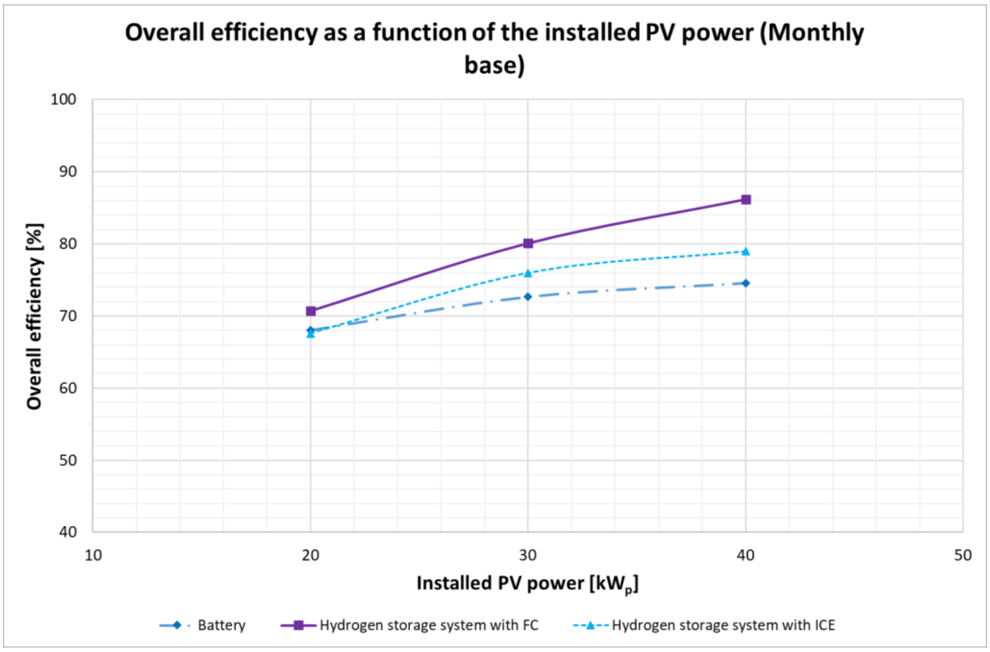

Figure 6.24. Overall efficiency of the system located in Syracuse.

6.5. Discussion of the obtained results by the energy balance on monthly base

Once all the cases have been analyzed, a comparison between the main performance parameters calculated with the energy balance on monthly base could be performed.

From the electrical point of view, also in this analysis, the plants with battery have better performances with respect those with the hydrogen storage systems, at the same installed PV power. However, due to the lower flexibility of the batteries, the gap resulting from yearly average calculation is reduced in monthly calculations. This is also due the possibility of a more flexible storage given by the hydrogen resulting in an increase of the performance of the system. The results show that the performance of the storage systems do not depend only by their correct balancing with the PV installed power, according to the daily power production, but also by their flexibility to be resilient to the weather conditions of the considered location, i.e. their capacity to store excess of electric energy production for more than one day without saturation and following the variation of power generation on one side, and power requests by the users on the other one.

For example, it is interesting the fact that sometime H-ICE could has better performances than H-FC and batteries, because it has less electric efficiency and higher heat production, so that it is able to convert more hydrogen for supplying the same quantity of electricity, but more heat, so allowing a better storage. So that, converting electricity into heat could be a new strategy for a better use of the batteries for PV generated energy storage. Storage strategies are out of the scope of this thesis, but previous consideration could be the base for future studies on residential green energy system.

Thus, it is possible to conclude that in monthly analysis, with the considered conditions, the hydrogen storage systems show better performance parameters than the battery, differently by the results obtained in the chapter 5. In particular, the hydrogen storage system with FC presents a better working functioning at low/medium PV installed power, while the hydrogen storage system with ICE at the high PV installed power.

7. Conclusions

The purpose of the thesis's work was to apply an energy analysis of RES systems applied in an energy community composed by 10 families. Considering the application sector, the PV plant was considered the most suitable green power generation system and this was coupled to solar water heating (SWH) system plus the auxiliary boiler for the TE supply, used just for the domestic hot water (DHW) production. Moreover, since one of the main problems linked to the RES energy generation is the mismatch between the production and the consumption, different energy storage strategies have been analysed:

- A conventional one based on batteries;
- A hydrogen storage based on a system formed by electrolyser, metal-hydride tanks hydrogen storage and a hydrogen fuel cell (H-FC) regenerative system with heat recover;
- A hydrogen storage system formed by electrolyser, metal-hydride tanks hydrogen storage and hydrogen fuelled internal combustion engine cogeneration unit (H-ICE).

In particular, these last two plants produce both electrical and thermal energy as the electrolyser and the FC/ICE are working. This generated heat is then matched with the produced thermal energy by SWH plant for the DHW production. Thus, the obtained systems are the so-called combined heat and power (CHP) ones. However, the chosen hydrogen systems configuration could be also compliant with the definition of poly-generation systems. This because, the stored hydrogen could also be used as fuel for mechanical energy generation or other purposes, like car refuelling. Moreover, at least in principle, metal hydrides storage could be used as heat pump or as thermally driven hydrogen compressor, although studies in these directions are at early stage, and this approach was not considered in this work.

As concern the analysis, this has been carried out firstly on yearly average basis energy data. Further, a sensitivity analysis has been carried out by changing the size of the PV power (20, 30 and 40 kW_p) and the geographical location of the residential building. In particular, three representative locations have been chosen: Milan, Rome and Syracuse for North, Centre and South Italy respectively. While the SWH system size has been maintained unchanged, according to the thesis's focus on the energy storage for damping the mismatch between generated and consumed power from PV.

Then, for each case, a design size is proposed for the electrical storage system. The design method is based on the maximization of the self-consumed energy, trying to minimize the dependency by the grid. At the end of the energy analysis, the main performance parameters of the different systems have been obtained and compared each other.

Later, on the basis of the designed storage systems, the monthly energy balance has been carried out. Thus, the seasonal variations of the produced energy by the PV plant and the consumed one by the users has been considered. This entails in more accurate results of the systems performance.

Therefore, at the end, a total of 54 energy balances analysis have been conducted, with the aim to calculate both the electric and overall (heat and power) self-sufficiency and systems efficiency for each case.

The results show that, despite the hydrogen-based storage systems have a lower electrical efficiency than the battery, they seem to have better overall performances if the possibility to work in cogeneration is considered. This is also due to the considered possibility of a seasonal storage of the hydrogen.

Thus, consideration on the obtained results open new question to be solved in future studies:

1. Due to the fact that hydrogen-based storage systems seem more efficient than batteries ones, they are able to carry out also economic advantages?
2. How much are important the storage strategies?
3. Today there is not a specific regulation for hydrogen-based storage system in residential application, is it necessary, or the existing regulation for methane and LPG can be applied?

Thus, although out of the thesis scope, some simple calculations about the systems costs are below reported in the Table 7.1. and Table 7.2. to try to give a roughly answer to the first question.

Table 7.1. Roughly estimation of the cost of the PV plant with battery and SWH system

	Milan			Rome			Syracuse			
PV plant										
Specific cost	1500									[€/kWh]
Installed PV power	20,0	30,0	40,0	20,0	30,0	40,0	20,0	30,0	40,0	[kWp]
PV cost	30000,0	45000,0	60000,0	30000,0	45000,0	60000,0	30000,0	45000,0	60000,0	[€]
Battery										
Specific cost	370,0									[€/kWh]
Installed capacity	63,7	112,6	161,5	79,4	119,2	159,0	88,0	149,2	210,3	[kWh]
Battery cost	23565,3	41662,0	59758,7	29378,0	44115,1	58822,6	32574,8	55189,2	77796,2	[€]
PV+B cost	**53565,3**	**86662,0**	**119758,7**	**59378,0**	**89115,1**	**118822,6**	**62574,8**	**100189,2**	**137796,2**	[€]
SWH system										
Specific cost	3000,0									[€/unit]
Installed capacity	10,0									[unit]
SWH system cost	**30000,0**									[€]
PV+B+SWH cost	**83565,3**	**116662,0**	**149758,7**	**89378,0**	**119115,1**	**148822,6**	**92574,8**	**130189,2**	**167796,2**	[€]
EE balance										
Average daily supplied EE	64,0	94,9	125,7	73,9	109,7	145,5	79,4	117,9	156,4	[kWh/d]
Specific EE cost	0,293									[€/kWh]
Average daily money saving	18,8	27,8	36,8	21,7	32,1	42,6	23,3	34,5	45,8	[€/d]
Annual money saving in EE	**6847,7**	**10143,7**	**13438,7**	**7906,4**	**11731,9**	**15557,3**	**8489,3**	**12606,7**	**16723,0**	[€/y]
PBT (EE)	**7,8**	**8,5**	**8,9**	**7,5**	**7,6**	**7,6**	**7,4**	**7,9**	**8,2**	[y]
TE balance										
Average daily produced TE	82,2			90,4			98,6			[kWh/d]
Specific TE cost	0,91									[€/m^3]
Average daily money saving	6,4			7,1			7,7			[€/d]
Annual money saving in TE	**2339,8**			**2573,8**			**2807,8**			[€/y]
PBT (TE)	**12,8**			**11,7**			**10,7**			[y]
Annual money saving (EE + TE)	**9187,5**	**12483,5**	**15778,5**	**10480,2**	**14305,6**	**18131,1**	**11297,1**	**15414,4**	**19530,8**	[€/y]
PBT (EE + TE)	**9,1**	**9,3**	**9,5**	**8,5**	**8,3**	**8,2**	**8,2**	**8,4**	**8,6**	[y]

Table 7.2. Roughly estimation of the cost of the PV plant with hydrogen-based storage system and SWH system.

	Milan			Rome			Syracuse			
PV plant										
Specific cost	1500									[€/kWp]
Installed PV power	20,0	30,0	40,0	20,0	30,0	40,0	20,0	30,0	40,0	[kWp]
PV cost	30000,0	45000,0	60000,0	30000,0	45000,0	60000,0	30000,0	45000,0	60000,0	[€]
Hydrogen S.S.										
EC specific cost	1500,0									[€/kW]
EC installed power	14,4	24,0	36,0	14,4	26,4	36,0	14,4	26,4	38,0	[kW]
EC cost	21600,0	36000,0	54000,0	21600,0	39600,0	54000,0	21600,0	39600,0	57000,0	[€]
FC-CHP specific cost	5000									[€/kW]
FC-CHP installed power	1,55	2,73	3,92	1,93	3,3	4,68	2,13	3,95	5,1	[kW]
FC-CHP cost	7750	13650	19600	9650	16500	23400	10650	19750	25500	[€]
MH specific cost	15									[€/kWh$_{H_2}$]
Maximum storable H_2 energy	923,91									[kWh$_{H_2}$]
MH cost	13858,7									[€]
H_2 S.S. cost	43209	63509	87459	45109	69959	91259	46109	73209	96359	[€]
PV+H.S.S. cost	**73208,7**	**108508,7**	**147458,7**	**75108,7**	**114958,7**	**151258,7**	**76108,7**	**118208,7**	**156358,7**	[€]
SWH system										
Specific cost	3000									[€/unit]
Installed capacity	10									[unit]
SWH system cost	**30000**									[€]
PV+H.S.S.+SWH cost	**103209**	**138509**	**177459**	**105109**	**144959**	**181259**	**106109**	**148209**	**186359**	[€]
EE balance										
Average daily supplied EE	37,74	48,57	59,24	41,26	53,66	66,07	43,14	56,49	69,84	[kWh/d]
Specific EE cost	0,293									[€/kWh]
Average daily money saving	11,1	14,2	17,4	12,1	15,7	19,4	12,6	16,6	20,5	[€/d]
Annual money saving in EE	**4036,1**	**5194,3**	**6335,4**	**4412,6**	**5738,7**	**7065,9**	**4613,6**	**6041,3**	**7469,0**	[€/y]
PBT (EE)	**18,1**	**20,9**	**23,3**	**17,0**	**20,0**	**21,4**	**16,5**	**19,6**	**20,9**	[y]
TE balance										
Average daily produced TE	104,94	122,61	140,13	118,88	122,61	140,13	130,44	152,53	174,61	[kWh/d]
Specific TE cost	0,91									[€/m^3]
Average daily money saving	8,2	9,6	10,9	9,3	9,6	10,9	10,2	11,9	13,6	[€/d]
Annual money saving in TE	**2987,4**	**3490,4**	**3989,2**	**3384,2**	**3490,4**	**3989,2**	**3713,3**	**4342,2**	**4970,7**	[€/y]
PBT (TE)	**10,0**	**8,6**	**7,5**	**8,9**	**8,6**	**7,5**	**8,1**	**6,9**	**6,0**	[y]
Annual money saving (EE + TE)	**7023,5**	**8684,7**	**10324,6**	**7796,8**	**9229,1**	**11055,0**	**8326,9**	**10383,5**	**12439,8**	[€/y]
PBT (EE + TE)	**14,7**	**15,9**	**17,2**	**13,5**	**15,7**	**16,4**	**12,7**	**14,3**	**15,0**	[y]

As concern the economical evaluation, the main parameter is the return-on-investment time (PBT). This could be roughly calculated as the ratio between the capital cost of the plant and average annual money saving. Thus, this represents the years needed to recover the initial investment. Instead, the average annual money saving is calculated as the product of the cost of the energy for that produced by the plant. Then, this represents the average cost of the energy that should be paid for buying it on the Italian energy market. However, in this analysis, the following approximations have been considered:

- The cost of the different technologies has been approximated in excess [32, 54, 55, 56, 57, 58, 59], without considering inflation or other financial charges for discounting.
- Both the electrical and thermal energy costs refer to those reported by ARERA, considering the first trimester of 2022 [60].

- The scale factor of the devices cost as a function of the design size is not considered. Indeed, costs should tend to increase by increasing the design parameters until to converge to a certain value, rather to linearly increase.
- Replacement costs of both batteries, every five years, and parts of hydrogen-based storage system are neglected. This because, until now, the lifetime of the electrolyzer, metal hydrides tank and FC is not exactly known.
- The case of hydrogen-based storage system with ICE is neglected. This because this kind of technology is not fully developed, thus the cost are still unknown.

Looking at the obtained results, by considering just the electric energy, the values of the PBT in the case of the PV plant with hydrogen-based storage system are about 2.5 times higher than in the case with battery. Indeed, considering both the electrical and thermal energy saving, the values of the PBT of the PV plant with hydrogen storage system become less than two time higher than in the case with battery. Thus, despite these results, the innovative storage solution would look interesting for future applications. This because the costs of both the electrolyzer and the FC are expected to decrease in the next 10 years, thus the PBT could also become lower than in the case of battery.

About the storage strategy, it could contribute to a better balance for all the considered systems. Probably also hybrid systems, i.e. hydrogen plus batteries, have to be considered for optimization. Moreover, it is expected that this optimization will depends strongly by the specific location.

Not the least, in the thesis a limitation to 750 geometric liters of hydrogen storage was considered, according to the current Italian fire prevention regulation. This regulation was born for LPG and methane applications. An hydrogen related regulation is needed as soon as possible to avoid that this mature technology will remain unexploited.

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