# A comparison of energy storage from renewable sources through batteries and fuel cells: A case study in Turin, Italy



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Abstract: The need for storage of energy produced from renewable sources is increasing in the last decades, due to uneven energy production from these sources and to the need to run systems located in off grid areas. In this paper, two alternative integrated power systems were taken into account and compared: one based on photovoltaic and hydrogen technology (electrolyzer coupled with a fuel cell), the other based on photovoltaic and batteries. The two power systems, designed for off-grid applications, were sized on the basis of load curves created starting from possible appliances in use of a family house, and on the photovoltaic energy production in the area of Turin, Italy. They have to provide 3 kW maximum power, with an average daily consumption of 10.25 kWh in winter, 8.96 kWh in spring and autumn and 8.62 kWh in summer. The two systems were compared from a technical and economical point of view and a preliminary Life Cycle Assessment analysis (LCA) was performed, in order to describe the environmental impact of the systems.
Being the fuel cell and the electrolyzer niche products from a commercial point of view, their costs are higher with respect to Li-ion batteries, therefore, power system based on the hydrogen technology results to be more expensive. However, from the environmental point of view the preliminary LCA results show that both electrolyzer plus fuel cell, and batteries have lower impacts with respect to other components, for example the solar panels.

Cover Letter

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Torino, 25/2/2016

Dear Editor,

Following your suggestions, I am re-submitting a paper for publication in Applied Energy:

**Energy storage from renewable sources: a case study in Turin, Italy**

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The paper contains new data on a comparison between two alternative integrated power systems: one based on photovoltaic and hydrogen technology (elctrolyzer coupled with fuel cells), the other based on photovoltaic and batteries. These systems were designed starting from the photovoltaic energy production in the area of Turin, Italy and load curves created from possible appliances in use of a family house in the same region. The two systems were compared from a technical and economical point of view and a preliminary Life Cycle Assessment analysis (LCA) was performed, in order to give an idea of the environmental impact of the systems.
In the introduction it is more clearly stated the knowledge gap that can be filled with the present article, i.e. the lack of papers that compare the hydrogen technology and the battery as energy storage systems using three parameters (system's sizing, costs analysis and LCA).
Moreover, a more complete survey of the literature was made, paying particular attention to papers published in Applied Energy and others top energy journals.

I look forward to hear from you.

Sincerely yours

Paola Rizzi

***Highlights (for review)**

Design and sizing of two power systems for off-grid applications in Turin area.
Comparison of energy storage systems: electrolyzer coupled with fuel cell and battery
Cost analysis show that power system based on hydrogen technology is more expensive
LCA shows that electrolyzer + fuel cell has lower impact with respect to solar panels

# Energy storage from renewable sources: a case study in Turin, Italy

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## Abstract

The need for storage of energy produced from renewable sources is increasing in the last decades, due to uneven energy production from these sources and to the need to run systems located in off grid areas. In this paper, two alternative integrated power systems were taken into account and compared: one based on photovoltaic and hydrogen technology (electrolyzer coupled with a fuel cell), the other based on photovoltaic and batteries. The two power systems, designed for off-grid applications, were sized on the basis of load curves created starting from possible appliances in use of a family house, and on the photovoltaic energy production in the area of Turin, Italy. They have to provide 3 kW maximum power, with an average daily consumption of 10.25 kWh in winter, 8.96 kWh in spring and autumn and 8.62 kWh in summer. The two systems were compared from a technical and economical point of view and a preliminary Life Cycle Assessment analysis (LCA) was performed, in order to describe the environmental impact of the systems.

Being the fuel cell and the electrolyzer niche products from a commercial point of view, their costs are higher with respect to Li-ion batteries, therefore, power system based on the hydrogen technology results to be more expensive. However, from the environmental point of view the preliminary LCA results show that both electrolyzer plus fuel cell, and batteries have lower impacts with respect to other components, for example the solar panels.

Keywords
Integrated power system, fuel cell, electrolyzer, battery, Life Cycle Assessment, costs analysis.

## 1. Introduction

In the last decades, energy related problems are becoming more stringent and there is an increased interest in renewable energy production methods [1-3]. One of the main problems of renewable resources is that they are subjected to variations in the production according to the hour of the day, the period of the year, etc. Therefore, it is necessary to store produced energy allowing its use after production. Energy storage has many attractive functions, such as: (i) helping in meeting peak electrical load demands, (ii) providing time varying energy management, (iii) alleviating the intermittence of renewable source power generation, (iv) improving power quality/reliability, (v) meeting remote and vehicle load needs, (vi) supporting the realization of smart grids, (vii) helping with the management of distributed/standby power generation, (viii) reducing electrical energy import during peak demand periods [4].

The criteria for the selection of solutions for the storage of renewable energy are still under debate, both for stationary and mobile applications [5]. In particular, it turns out that a combination of technical, economic and environmental parameters have to be considered [6]. So, it is clear that a general solution cannot be identified and specific case studies have to be considered. In fact, the best solution strongly depends on the size and on the boundary conditions of the specific application, which have to be defined for both renewable energy production and storage. For this reason, the development of a database of case studies can be the starting point for the definition of general strategies to be applied for the future massive introduction of renewable energy sources in the electric grid systems.

A good storage system should be useful also if the system is located in a remote off grid area, like mountain lodges or small islands. In the case of the former, in fact, according to two studies in alpine regions of Italy (Valle d'Aosta and Friuli Venezia Giulia), around 60% of mountain lodges are not grid-connected. In Valle d'Aosta, 54% of the lodges use diesel generation systems to produce all or at least part of the electricity needed (28% for example use diesel generation combined with photovoltaic panels) [7] and in Friuli Venezia Giulia 58% of lodges are not grid connected, of which 42% using diesel generation systems [8]. On the other hand, in Italy there are 12 small islands that are not grid connected and, still nowadays, are producing the greatest part of the electricity needed with diesel generation systems. Since the latter are not efficient and the lorries transporting the fuel can only be carried on special ships, this way of generating electricity is expensive and polluting [9], with poor power quality performance and high maintenance costs. The problem is worsened by the legislation and administrative barriers that obstacle the diffusion of renewable energy production technologies. This is not only the case of Italian islands, but also that of many others spread all over the world [10]. Therefore, for the development of remote regions, various integrated power systems were suggested in the last few years in the literature. In various studies, photovoltaic panels or wind turbines are combined with batteries to store energy and provide it to several households, but they can be used also for irrigation systems, such as for olive orchards irrigation [11-16].

Other studies are related to the use of fuel cell-based systems, i.e. systems composed by fuel cell (FC), electrolyzer and hydrogen tank, that can be used for energy storage [17,18]. These hydrogen-based storage systems are sometimes coupled with renewable energy sources, such as wind turbines or photovoltaic panels, that are mainly used to provide energy to the electrolyzer [19-23]. In some cases a comparison of the storage energy systems used (i.e. FC and batteries) are made [23].

Different integrated systems are described: in [18] the study was devoted to the integration of a hydride tank, where LaNi4.8Al0.2 was used to store $H_2$, with a PEM-FC; this systems gives 6h autonomy delivering a total energy of 4.8 kWh. In the island of Utsira in Norway [20] a wind/hydrogen energy system was installed, composed by wind turbine, electrolyzer, hydrogen storage in form of pressured gas and a PEM-FC. The system gives 2–3 days of full energy autonomy for 10 households on the island. Lavorante et al. [17] proposed an integrated power system for remote communities, composed by electrolysers, cylinders tanks and PEM-FC. The system has an autonomy of 16h and a power of 53 kW. In a pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland [21], a comparison of various renewable and non-renewable energy sources and energy storage methods was presented, for a remote house having an energy consumption of 25 kWh per day with a 4.73 kW peak power demand. It was found that, even if a wind–diesel–battery system is the most suitable solution at present, a wind–fuel cell system would become a superior choice with a reduction of fuel cell cost to 15% of its current value.

Silva et al. [23] described a pilot-project set up in an environmental protection area, in Brazil, focusing the study on technical and cost issues. As in the [21] study, it was found that fuel cell and electrolyzer are costly and the best option, from the cost point of view, for storing energy from photovoltaic systems is still the use of batteries.

The use of fuel cells is also a valid solution for combined heat and power generation (CHP) [24 - 26]. The environmental impact and energy consumption of a power system can be adequately evaluated by performing a Life Cycle Assessment analysis (LCA), a method that takes into account the environmental impact of a product or a process over its full life cycle (from “cradle to grave”). Different examples are reported in literature in which various $H_2$ production methods are compared [1, 27-29].

In this work, two alternative integrated power systems will be taken into account and compared: one based on photovoltaics and hydrogen technology, the other based on photovoltaic and batteries. The two systems will be compared from a technical and economical point of view and a preliminary Life Cycle Assessment analysis (LCA) will be performed, in order to evaluate the environmental impact of the systems, finding out which components are more critical from this point of view. It is the first study of this kind for the area of Turin. Most studies are limited to the system’s sizing [10,11,14-19,22,26] and some of them consider also cost analysis [12,20,21,23,24]. LCA is instead considered only in very few studies [13,25,30] and among these, only that of Balcombe et al. [24,25], considers all the three aspects of the CHP system. The present study aims to take into account system’s sizing, LCA and cost analysis together for the first time for the selected systems.

## 2. Possible application

The area of Turin was chosen for this study for the multiplicity of scenarios it offers, i.e. grid connected urban area and small villages and remote mountain lodges on the alpine chain that cannot count on a grid connection. Since the electricity demand of these realities can be quite different one from another, as an example of a possible application, a family house with 3-4 inhabitants, located in Turin has been chosen for a more detailed study.

### 2.1 Power load curves and average electricity consumption of a family

In order to create a realistic load curve of a family house, some commercial appliances were chosen and their consumptions were taken from datasheets; when more than one value was reported, the highest was chosen. The appliances taken into account are: fridge, oven, washing machine, dishwasher, air conditioner, toaster, hair dryer, vacuum cleaner, coffee machine, LED television, and lighting. For drawing the load curves, it has been necessary to make some assumptions concerning the house and the habits of the family, i.e. the number and type of lamps per room, the use of the illumination during the year (including seasonal variations), changes in the use frequency of some devices along the year, e.g. television switched on for fewer hours in summer than in winter. Furthermore, some devices are typically used only in some periods of the year, like air conditioning. Three load curves have been drawn: one for winter, one for spring and autumn (considering these seasons similar from the electricity consumption point of view) and one for summer. These are represented in Fig. 1.

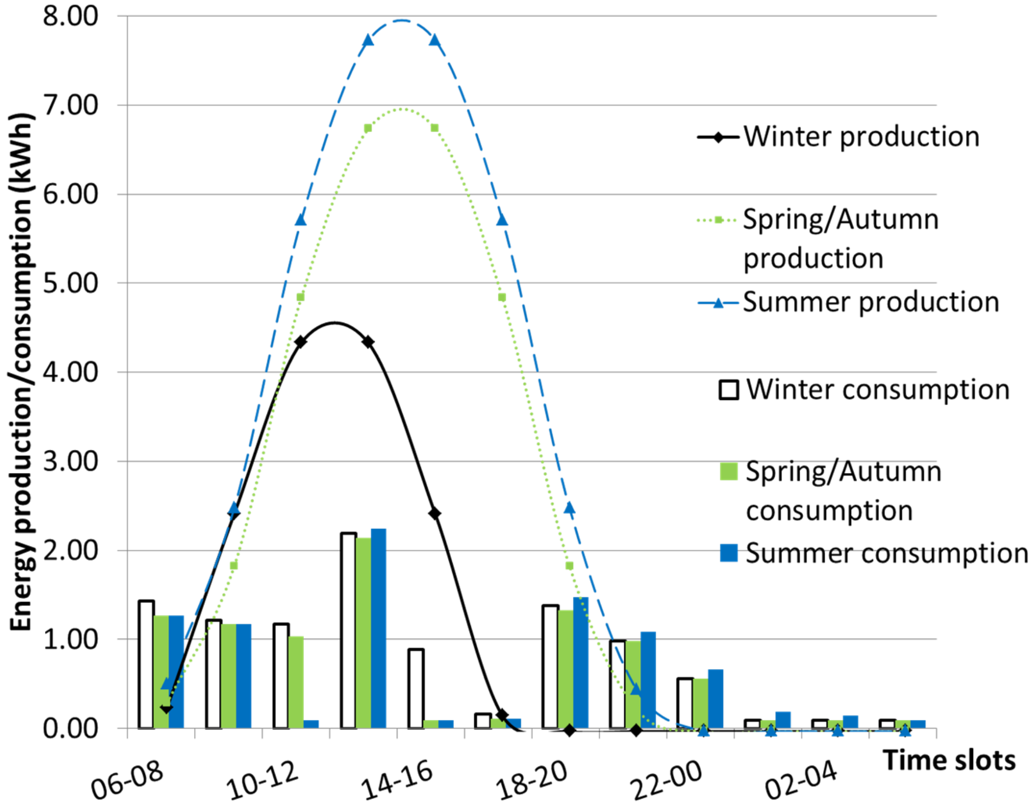


**Fig. 1** Energy production from photovoltaics in winter, spring/autumn and summer (plain, dotted and dashed lines, respectively), and electricity consumption in the same periods (framed for winter, light for spring/autumn and dark for summer).

The load curves have a common trend: starting with a peak in energy demand between 6 and 8 (1.43 kWh, 1.27 kWh and 1.27 kWh for winter, spring/autumn and summer, respectively), electricity consumption decreases, afterwards. A second peak can be clearly seen between 12 and 14 (2.19 kWh, 2.14 kWh, 2.24 kWh for winter, spring/autumn and summer, respectively), this is in all cases the highest of the day and it is followed by a rapid decrease in power demand. Between 18 and 20 another peak is reached (1.38 kWh, 1.33 kWh, 1.48 kWh for winter, spring/autumn and summer, respectively). From midnight to 6, energy demand remains at a minimum value (0.09 kWh) that is due to the electricity consumption of the fridge, except during summer, when the air conditioner is switched on, and the minimum of 0.09 kWh is reached only between 4 and 6. The differences between the curves are mainly due to lighting and air conditioning. During winter, in fact, days are shorter and cloudier, therefore the inhabitants of the house are supposed to switch the lights on also during the day. During summer it was assumed to be light enough coming from outside thus allowing the lights to be kept switched off, but the air conditioning switched on. Spring and autumn are considered as intermediates between power demand in winter and in summer.

From loads curves, the average daily consumption of a family of 3-4 members was determined to be 10.25 kWh in winter, 8.96 kWh in spring and autumn and 8.62 kWh in summer. These data can be compared with those provided by statistic studies, which give not differentiate results for seasons and that sometimes are very different one from another. These can in fact depend on the part of Italy they are referred to: considering, for example, the electricity consumption for domestic use for Italian provincial capitals provided by ISTAT (warehouse of statistics currently produced by the Italian National Institute of Statistics) in 2012, the highest daily consumption of electricity was registered in Olbia (17.56 kWh) and the lowest in Trento (9.80 kWh), while in industrial cities like Milan and Turin the electrical consumption was 11.24 kWh and 12.44 kWh, respectively [31].

On the other hand, a study by the Italian Regulatory Authority for Electricity Gas and Water reports the value 7.40 kWh/day, which represents an average on family consumptions of electricity in Italy [32] .The difference between these values is due to the sometimes big differences among families living in different parts of Italy, due to climate, habits and number of electrical appliances.

The values calculated from load curves are in agreement with data reported in literature, therefore, an average value of 10.25 kWh/day was choose to size the systems.

To build a well-functioning system it is not only necessary to know the total amount of electricity needed in a day, but also the sizes of the peaks of consumption. Therefore, considering the load curves, the system was sized for providing 3 kW load, which is also the most common power for electricity supply for Italian families.

### 2.2 Irradiation data

The solar resource was considered for the area of Turin. The irradiation data taken from the online database by JRC [33] show that the annual average solar radiation is 4.80 kWh/m$^2$/day for Turin, which is an encouraging value for electricity production from photovoltaics.

To define the correct sizing of the system, however, it is necessary to consider also seasonal fluctuations: the monthly average irradiation data, taken from the database by JRC [33], are shown in Fig.2. The difference between the irradiation values of summer and winter (6.59 and 2.79 kWh/m$^2$/d for July and December, respectively) is significant: for the right sizing of the system the worst conditions have to be kept in mind, i.e. the winter months, in particular December.

Thus the system was sized basing on the average daily irradiation data of December. For comparison, however, the irradiation data of July and April were considered as well, as examples of summer and spring irradiation, respectively. The irradiation data of April are quite similar to that of September, as can be seen in Fig. 2.

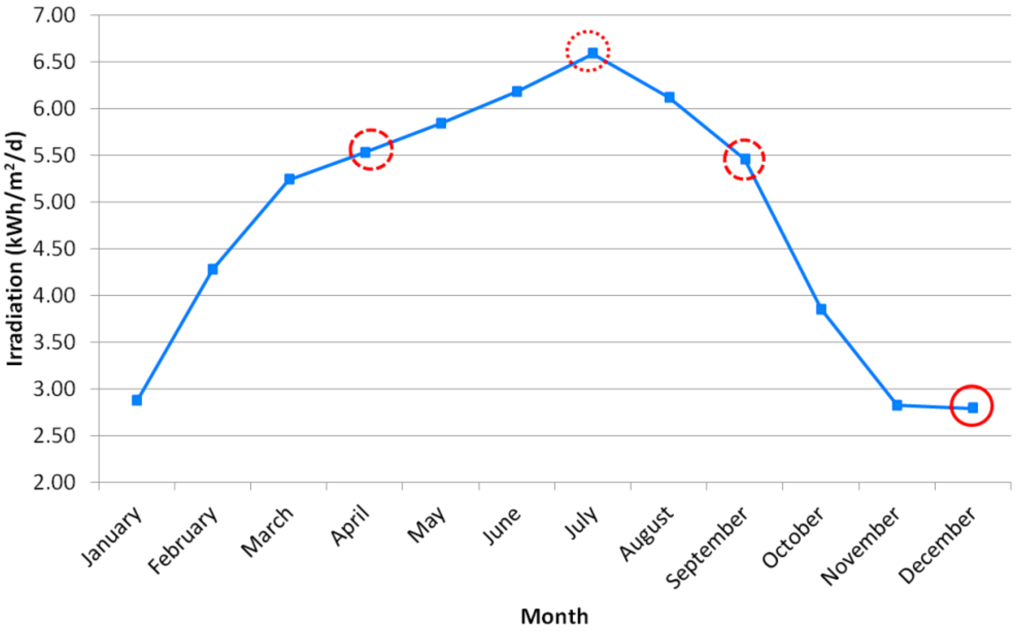


**Fig. 2** Monthly average irradiation data selected from the database by JRC [33]. In the circles the irradiation data considered are highlighted: December (plain circle), July (dotted circle), April/September (dashed circle).

## 3. System description

For this study it was chosen to size the systems for being stand alone. In this case it is necessary to store not only the amount of energy needed for one day, but also for a second day, in case that the amount of energy produced by the solar panels is not enough to provide energy for the house and charge the storage system (for example in case of rainy weather).

The two systems designed in this work have in common the use of photovoltaic panels for production of energy. Moreover, in order to size the systems, the following data have been used:

Average daily consumption: 10.25 kWh, as detailed in paragraph 2.1;

Self-sufficiency of the system: 2 days;

Maximum power load: 3 kW at 220 Vac;

Load curve for winter months (Fig. 1);

Technical data for a single photovoltaic panel: power 250 W each; voltage 30.2 Vdc; current 8.2 A; surface area 1.65 $m^2$; efficiency 15.2%.

### 3.1 Sizing of the system with battery storage

In order to cover the two days consumption, it is necessary to size the storage system, not only because during the night solar panels do not produce energy, but also because the weather conditions could affect the energy production. The photovoltaic system thus must generate, apart from the daily load requirement, a surplus of energy for charging the batteries for the second day.

#### 3.1.1 Sizing of the photovoltaic array

The first point of the sizing is to calculate the daily energy production for a single panel of 250 W peak power. Since the load curves of Fig. 1 are divided in time slots, it has been considered useful to use the same approach for the daily energy output of a solar panel.

This has been done using the global irradiance for Turin ($W/m^2$) taken from [33]. These values in fact, multiplied by the surface area of the single panel and its efficiency, give the electricity production in a certain time slot. Summing up the production of the panel during all time slots, its daily production results. Since the average daily production in a winter day is 0.7 kWh for a single solar panel, to produce the average daily electricity consumption (10.25 kWh), 15 solar panels are needed. A surplus of energy to charge the batteries is produced by five more panels.

In Fig. 1 the electricity production curves during average winter, summer and spring/autumn days, using 20 solar panels are compared with the electricity consumption.

The system thus has 20 photovoltaic panels, with a peak power output of 250 W each, connected to a commercial charge controller with the following features: efficiency about 96%; input power 3.5 kW, 48 Vdc.

To supply the right voltage to the charge controller, the following configuration is adopted:

i) 3 strings connected parallel, each composed by 4 panels connected series, providing a 120 Vdc, 24 A current;

ii) 2 strings connected in parallel, each composed by 4 panels in series, providing a 120 Vdc, 16 A current.

With this configuration, it is possible to use 2 standard commercial charge controllers, as the power for a single channel is less than 3.2 kW and the voltage is less than 150 Vdc.

### 3.1.2 Sizing of the battery storage

The battery pack should be designed to store 20.5 kWh for 2 days self-sufficiency (10.25 kWh each day). Commercial batteries with a capacity of 12 Vdc 150 Ah are connected to a commercial inverter, with the following features: efficiency about 98%; input power: 3.2 kW, 150 Vdc.

Since a 48 Vdc inverter is chosen, the final system is composed by 12 batteries, supplying 48 Vdc at 450 Ah.

In Fig. 3 a detailed representation of the described system is shown in the highlighted area. The detailed list of its components is: 20 Polycrystalline silicon solar panels with nominal power output of 250 W each, connected in series in strings (4 panels per string); the strings are grouped by 2 and 3 in parallel; 2 solar controllers, each one connected to a series of panel strings; 12 Lithium batteries (LiFePO4) with power output of 12 Vdc 150 Ah each; a 3 kW inverter converting the 48 Vdc from the battery pack or the photovoltaic panels in 220 Vac required by the load.

## 3.2 Sizing of the fuel cell-based system

Apart from what described previously, the sizing of the system has been carried out starting from the following data:

1) Technical data of the electrolyzer

- maximum power supply: 5 kW;
- Hydrogen production: 1000 l/h.

2) Technical data of the PEM (Proton Exchange Membrane) fuel cell

- maximum power output: 3 kW, 48 Vdc;
- Hydrogen consumption: 733 l/kWh.

The hydrogen produced is stored in gas cylinders at a pressure of 30 bar, which corresponds the outlet pressure of the electrolyzer.

### 3.2.1 Sizing of the photovoltaic array

The photovoltaic system must produce a surplus of energy for charging the cylinders with hydrogen, apart from what is required by the loads during the day, which is provided directly by the solar panels. Since the energy requirement between 18 and 6 (i.e. when the solar panels do not produce electricity), is about 4.5 kWh, the minimum quantity of hydrogen produced during the day must provide this energy.

In particular, the fuel cell has a hydrogen consumption of 733 l/kWh which means that to supply 4.5 kWh, 3300 l of hydrogen are necessary.

Since the electrolyzer requires 5 kWh to produce 1000 l of hydrogen, the energy needed to produce 3300 l is given by:

$$(3300 \text{ l} * 5 \text{ kWh})/1000 \text{ l} = 16.5 \text{ kWh}$$

Thus, the total energy request is given by the electricity consumption of the electrolyzer, and that of the load between 6 and 18 (the energy required between 18 and 6 is provided by the fuel cell via the stored hydrogen):

$$\text{Total energy request (kWh)} = (10.25 - 4.5) + 16.5 = 22.25 \text{ kWh}$$

The photovoltaic array must be sized on this request. Being the daily winter production of the solar panel 0.7 kWh, 32 photovoltaic panels are needed. The panels are connected to a commercial solar controller with the following features: efficiency: about 96%; input energy: 3.5 kW, 48 Vdc.

To supply the right voltage to the charge controller, the following configuration is adopted: 3 strings connected parallel, each composed by 4 panels connected series, providing a 120 Vdc 24 A current; 3 strings connected parallel, each composed by 4 panels connected series, providing a 120 Vdc 24 A current; 2 strings connected in parallel, each composed by 4 panels in series, providing a 120 Vdc 16 A current.

With this configuration it is possible to use 2 standard commercial charge controllers, as the power for a single channel is less than 3.2 kW and the voltage is less than 150 Vdc.

### 3.2.2 Sizing of the hydrogen storage

The amount of energy stored for two days is 20.5 kWh. Since the fuel cell requires 733 l/kWh, 15027 l of hydrogen have to be stored.

Using standard cylinders for gas compressed at 30 bar (pressure of $H_2$ produced by the electrolyzer) with an internal volume of 50 l, the total number of cylinders needed is 10. Since standard cylinder bundles are composed by 12 tanks, 2 additional cylinders are added to the system.

In Fig. 3 a detailed representation of the system described is shown: the structure is the same as that of the other system (in the highlighted area), with some additional components. The detailed list of components is: 32 polycrystalline silicon solar panels with nominal power output of 250 W, connected in series in strings (4 panels per string); the strings are grouped by 2 and 3 in parallel; 3 solar controllers, each one connected to a series of panel strings; 4 $LiFePO_4$ batteries with power output of 12 Vdc 75 Ah each; a 3 kW inverter converting the 48 Vdc from the battery pack or the photovoltaic panels in 220 Vac required by the load; 12 type II gas tanks with a capacity of 50 l each, made aluminium alloys; a 5 kW alkaline electrolyzer; a 3 kW PEM fuel cell; an 80 l water tank for the electrolyzer. The latter is equipped with a rain water recovery system.

It can be noticed that the system with the fuel cell needs 12 additional solar panels with respect to the system with batteries. This is due to the low efficiency of the electrolyzer, which needs 5 kW power input in order to produce the hydrogen needed by the fuel cell to provide the 3 kW power output required by the load.

In Fig. 3 the battery pack has been highlighted in the dark framed area since both systems need it, but with different power features.

For both systems the possibility of sending electricity in excess to the grid is represented in Fig 3. This is the case if the systems are connected to the grid, but if they are located in remote off grid areas, the electricity in excess is sent to a load bank.

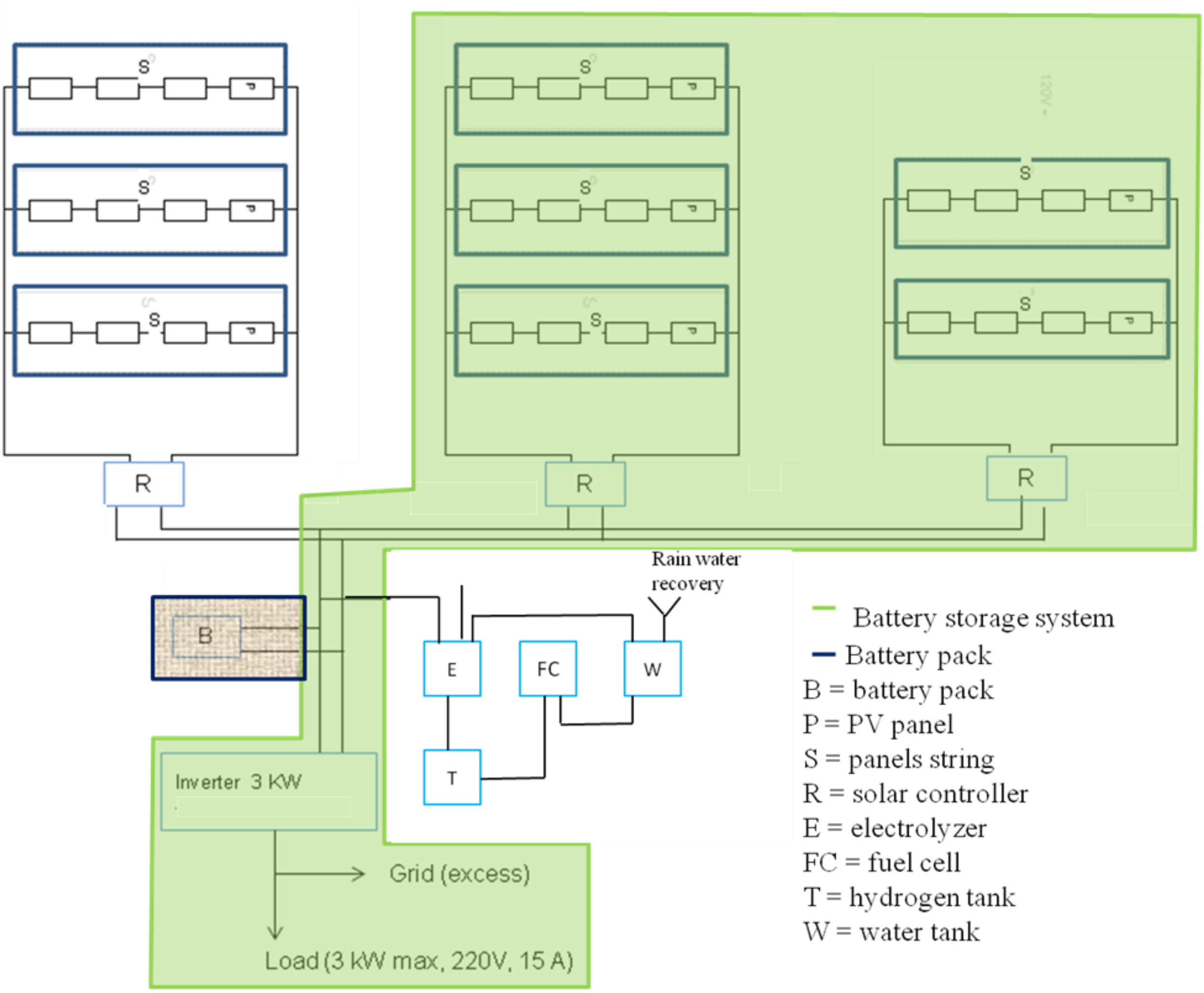


**Fig. 3** Scheme of the integrated systems: in the highlighted area the components of the system with battery storage are visible. The system with hydrogen storage is composed of the components in the highlighted area, to which an additional photovoltaic array and the electrolyzer+fuel cell device are added. The battery pack in the dark-framed area is used by both systems, but with different size.

## 4. Cost analysis

Knowing the correct size of the systems, it is possible to estimate costs of the components, in order to establish which system is more competitive from an economical point of view. The costs of the commercial devices supposed to be used in the construction of the two systems of Fig. 3 are listed in Tab. 1 and Tab. 2.

| **Components** | **Price per unit (€)** | **Total price (€)** | **Weight on the total price (%)** |
|---|---|---|---|
| Solar Panel (x 20) | 173 | 3460 | 14 |
| Solar controller (x 2) | 500 | 1000 | 4 |
| Batteries (x 12) | 1450 | 17400 | 72 |
| Inverter (x 1) | 2500 | 2500 | 10 |
| **Total price** | **24360** | | |

**Tab. 1** Price of single components for the system with battery energy storage and percent weight on total price of the system.

| Components | Price per unit (€) | Total price (€) | Weight on the total price (%) |
|---|---|---|---|
| Solar Panel (x 32) | 173 | 5536 | 11 |
| Solar controller (x 2) | 500 | 1500 | 3 |
| Batteries 12V 50 Ah (x 2) | 487 | 974 | 1 |
| Batteries 12V 100 Ah (x 2) | 958 | 1916 | 1 |
| Inverter (x 1) | 2500 | 2500 | 5 |
| Electroself 3 air (x 1) (alkaline electrolyzer + PEM fuel cell) | 30000 | 30000 | 60 |
| Gas cylinders (x 12) | 620 | 7440 | 15 |
| **Total price** | **49866** | | |

**Tab. 2** Price of single components for the system with electrolyzer + fuel cell and percent weight on total price of the system.

The prices reported are only relative to the devices and do not include mounting and installing costs. Furthermore, some complementary devices are not considered here, for example the steel structures on which panels are typically set on roofs, and the connection cables. These objects however do not represent a significant expense if compared to the main components of both systems.

It is immediately noticeable that in both cases the storage unit corresponds to more than 50% of the total cost of the system. Furthermore, in the case of the system using a fuel cell, the gas cylinders represent a significant expense.

Considering the total price of the systems, the one with battery storage is certainly the most competitive between the two, since its price is about half of that of the other. In considering these prices, however, one must take into account that the two systems, and storage technologies in particular, have different levels of commercial diffusion. Kits with solar panels, batteries, inverter and charge controller are easily available on the market, because this technology is already widespread and thus prices are more competitive with respect to a fuel cell.

This is not the case of the other system, using electrolyzer and fuel cell. These two devices are in fact still not produced on large scale, unlike batteries, so that production process is expensive and the devices are thus made less competitive.

## 5. Preliminary LCA analysis

LCA is a tool for the assessment of potential environmental impacts of products and services along the whole life cycle (cradle-to-grave approach), from the extraction of raw materials and fuels to the production of the investigated objects and their disposal or recycling [34]. The LCA basically consists of four steps [35].

**Goal and Scope Definition:** the investigated product, the data sources and system boundaries are described and the functional unit is defined. This is the reference to which all the in- and outputs are related;

**Inventory Analysis or life cycle inventory (LCI),** which involves data collection and calculation procedure to quantify relevant inputs and outputs.

**Life cycle impact assessment (LCIA):** the potential impacts of the in- and outputs of the Inventory Analysis are then determined by the Impact Assessment which categorizes and aggregates the environmental interventions. For that purpose, impact categories, such as global warming, are defined and characterization factors calculated which determine the contribution of different substances to that particular impact category.

**Interpretation:** the findings from the inventory analysis and the impact assessment are combined to give recommendations or draw conclusions. This last step is optional [36].

### 5.1 Goal and scope definition

The goal of this study is to get an overview on the environmental impacts of the energy production and storage systems described. It must be pointed out that this is only a preliminary study that does not mean to compare the two systems in order to establish which one is more competitive from an environmental point of view, but simply to show how the total impact is divided between the components identifying bottlenecks.

The functional unit chosen is equal to 3 kW, as this is the load required from the system by the application.

The study was carried out by means of the commercial SimaPro 8.1 software [37]. Within this software, the impact assessment method chosen was Impact 2002+ [38].

### 5.2 System Boundary

LCA is conducted by defining product systems as models that describe the key elements of physical systems. The set of criteria specifying which unit processes are part of a product system is called "system boundary" [39].

This analysis is focused on the production processes of the devices composing the two systems, considering raw materials (extraction and transport to the factory), electricity required for the various steps of production, and the infrastructure. Process waste is considered as well, together with the emissions to air.

### 5.3 Life Cycle Inventory (LCI)

The system boundary defines the unit processes to be included in the system. A model of the product system is conceived to represent the interaction of the product system with the environment. The model is commonly programmed in a dedicated LCA software tool and covers each step of the life cycle from the raw material extraction through to the products end of life in a series of interconnected steps called processes. Interaction with the environment is represented as elementary flows crossing the system boundary, e.g. resources taken from nature and introduced into the product system or emissions arising from combustion, physical, thermal or chemical conversion processes which are vented into the environment. The elementary flows which make up the interaction of a product system with the environment are compiled. This compilation is referred to as the Life Cycle Inventory (LCI) [40]. Due to the difficulty of finding data on the production of the different devices directly from manufacturers, they were taken from the Ecoinvent database [41]. Since on the latter it was not possible to find exactly the components of the systems studied, in some cases similar products were considered, while in other cases other approximations were made. In Tab. 3 the list of system components and approximations are shown.

| **Components** | **Data used** |
|---|---|
| Polycrystalline silicon solar panel 250 W (20 for the battery-based system and 32 for the fuel cell-based system) | Polycrystalline silicon solar panel 210 W |
| $LiFePO_4$ batteries 22 kWh | $LiMn_2O_4$ battery for electric vehicle 2 kWh |
| PEM Fuel cell 3 kW | PEM fuel cell 2 kW |
| Alkaline electrolyzer 5 kW | PEM fuel cell 2 kW |
| Aluminum gas tanks (12 x 50 l) | Drawing of a wrought aluminum alloy |
| Inverter 3000 W | Inverter 2500 W |
| Solar controller | Electric scooter controller |
| **Auxiliary components for fuel cell system** | |
| Water tank (80 l) | Molding of bottle grade PET granulate (6 kg) |
| Support structure for PV panels | Galvanized steel (356.4 kg) |
| Connection cables | Connector cable for computer (145 m) |
| Li-ion batteries for startup (3.6 kWh) | Li-ion battery for electric vehicle |
| Valves, pressure regulators, pressure transmitter | Stainless steel (1.1 kg) + average metal working for manufacturing of a chromium steel product<br>Brass (0.6 kg) + Brass casting |
| Tubing | Chromium steel pipe (0.6 kg) |
| **Auxiliary components for battery system** | |
| Support structure for PV panels | Galvanized steel (222.7 kg) |
| Connection cables | Connector cable for computer (100 m) |

**Tab. 3** System components and approximations considered for this study.

The PV panels reported in the Ecoinvent database are formed by the same amount of cells of the same surface as the ones considered in this study. They have also a very similar nominal power.
The use of the PEM fuel cell to approximate the electrolyzer is due to the unavailability of data on the alkaline electrolyzer. This approximation will be further discussed later (paragraph 5.5).
As already mentioned in paragraph 3, the fuel cell-based system needs an additional photovoltaic array, this is the reason for the increased amount of the galvanized steel of the support structure and the increase of the length of cables with respect to the battery-based system.

### 5.4 Impact assessment

The large number of resources and emissions that make up the LCI is translated into a handful of environmental impact categories in the Life Cycle Impact Assessment (LCIA) step. Mandatory elements in the LCIA are classification and characterization.
Classification is the assignment of the various emissions into impact categories. Most elementary flows can be assigned to one impact category, but in some cases a single attribution is not possible. In these cases, emissions are assigned to all impact categories they have impact on.
Characterization means the definition of how much impact an emission has with regard to a pre-defined reference substance of an impact category. This is expressed by means of a characterization factor [42].
For this study, the impact categories chosen are global warming potential (GWP) and Non Renewable Energy. These were evaluated using Impact 2002+ method [38].

### 5.5 LCA results and discussion

In Fig 4 the impacts in percent of the two systems are shown for global warming potential and non-renewable energy.

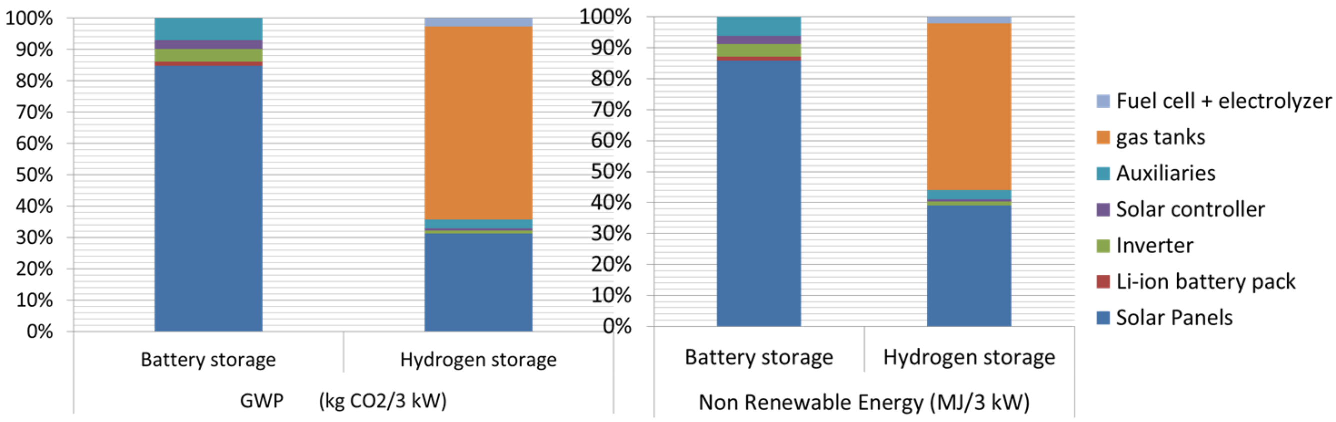


**Fig. 4** Global warming potential and non-renewable energy for of the two systems.

The solar panels have a significant impact on both systems, 81% and 30% GWP, 80% and 37% Non-Renewable Energy, respectively for the battery-based and for the fuel cell-based system. According to Jungbluth et al [43], the impact of a silicon-based solar panel is mainly due to the highly energy intensive purification process of silicon. The authors also point out that the PV sector is growing rapidly together with the technology involved. It is thus possible that the high impact of Si-based solar panels will be significantly reduced within few years thanks to production process improvements.

In the fuel cell-based system the highest impact is given by the 12 gas tanks (61% GWP and 52% Non-Renewable Energy). The tanks are made of aluminum based alloys, characterized by a high impact due to the purification process of aluminum and further metal working processes. This impact would be easily reduced using other types of tanks to store the hydrogen produced by the electrolyzer, or simply changing their size.

It is noticeable that the fuel cell and electrolyzer have a very low impact on both categories (3% GWP and 2% Non-Renewable Energy). The main contributor to the impact of a PEM fuel cell is the platinum used for the catalyst, as shown in other studies on fuel cell stacks [36,42].

As already mentioned in paragraph 5.3, the alkaline electrolyzer was approximated to a PEM fuel cell, which is similar to a PEM electrolyzer. However the amount of platinum group metals is lower in an alkaline electrolyzer with respect to a PEM electrolyzer. In fact only the cathode active material is constituted by a mixture of Pt, C and Ni, while the anode active material is composed by a mixture of Ni, Co and Fe (while in the PEM electrolyzer the only active materials are Platinum and Iridium for cathode and anode respectively) [44].

It is thus possible that the impact of the alkaline electrolyzer is overrated with this approximation. The low impact of an electrolyzer is confirmed in literature [45] for a system composed by a photovoltaic system and an electrolyzer in which over a total $CO_2$-equivalent emission of 0.0139 g/s, only 0.0007 g/s are due to the electrolyzer. Another LCA study on a wind power plant [46] which considers manufacturing and operation of the system, electrolysis, hydrogen compression and storage, shows that just 4% of the total energy equivalent and of the total $CO_2$-equivalent emission are due to the electrolyzer. In a LCA by Khan et al. [30] on a wind-fuel cell system, the values of GWP reported for the fuel cell are around 19.90 g CO2/kWh and those of the electrolyzer are around 11.14 g CO2/kWh over a total of 41.08 g CO2/kWh for the integrated system. These values can slightly change if different inventory data are used, referred to different power generation sources; this variation in the GWP values highlights their sensitivity to power generation mix sources used for the production of the integrated system and can explain the variability of results reported in literature.

Also the batteries for the battery-based system have a small effect on the total impact for both categories (1% for both). According to studies on $LiMn_2O_4$ batteries [47,48], the biggest contribution to the impact comes from the cathode material, followed by the anode material. This impact can be reduced improving manufacturing process, but also recycling of the materials at the end of the life of the battery. This is confirmed by another study [49], which considers more Li-based chemistries: the production of the cathode and anode materials represents a significant slice on the impact of the whole battery, in particular because of the use of metals like chromium, cobalt and nickel. Another important point, according to this study, is the use of steel and aluminium for the battery casing: the authors recommend the reduction of the percent by mass of these components. Also the fuel cell-based system needs batteries for start-up, these have been grouped into the "auxiliaries" because their energy is used only for the fuel cell, and they do not contribute to the energy storage for the house.

The auxiliaries give a marginal contribution to the impact of the battery-based system (7% GWP and 6% Non-Renewable Energy) and to that of the fuel cell-based (3% on both indicators). The main contributor to this impact is the hot dip galvanized steel used for the support structure, followed by the cable, and in particular the amount of copper used for its production.

## 6. Conclusions

Two systems for renewable energy production and storage applied to a family house located in Turin have been studied under different aspects. The main difference between the two is the storage system, but after the sizing step some other differences appear. The system based on hydrogen storage has in fact the highest number of solar panels, due to the energy requirement of the electrolyzer. This has an effect on the cost of this system, which is higher than that of the other system in exam. This is however due mainly to the electrolyzer and the fuel cell, which still represent niche products from a commercial point of view. From the environmental point of view, however, the preliminary LCA results suggests that the two devices seem to have lower impacts than other components of the systems, for example the solar panels and the gas cylinders.

The system based on Li-ion battery storage is a more mature technology than the hydrogen-based storage. System like the former are currently sold in form of kits, including all components; this makes its cost more competitive than that of the hydrogen-based system.

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## References


[1] S.E. Hosseini , M.A. Wahid, Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development, Renewable and Sustainable Energy Reviews 57 (2016), 850–866.

[2] A. Sherwani, J. Usmani, Life cycle assessment of solar PV based electricity generation systems: A review, Renewable and Sustainable Energy Reviews 14 (2010), 540-544.

[3] B. Shaffer, , B. Tarroja, S. Samuelsen, Dispatch of fuel cells as Transmission Integrated Grid Energy Resources to support renewables and reduce emissions, Applied Energy 148 (2015), 178–186.

[4] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy 137 (2015), 511–536.

[5] R.A. Huggins, "Energy Storage: Fundamentals, Materials and Applications", Springer (2015).

[6] "Commercialisation of energy storage in Europe", The Fuel Cell and Hydrogen Joint Undertaking (2015), available at http://www.fch.europa.eu/sites/default/files/CommercializationofEnergyStorageFinal_3.pdf

[7] R. Beltramo, S. Duglio, A. Giovinazzo, Produzione di energia elettrica e fattori inquinanti nei rifugi alpini della Valle d'Aosta, Acts of the XXII National Congress on study of commodities, department of economics RomaTre, Roma, 2006.

[8] Project Alpenlabel, Education and information manual for mountain lodge's managers, 2008, ARPA FVG.

[9] A. Codegoni, L'isola diventa rinnovabile. Qualenergia 1 (2013), 38-40.

[10] G.J. Osório, E.M.G. Rodrigues, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, New control strategy for the weekly scheduling of insular power systems with a battery energy storage system, Applied Energy 154 (2015), 459–470.

[11] R. Dufo-López, J.M. Lujano-Rojas, J.L. Bernal-Agustín, Comparison of different lead-acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems, Applied Energy, 115 (2014), 242-253.

[12] D.O. Akinyele, R.K. Rayudu, N.K.C. Nair, Development of photovoltaic power plant for remote residential applications: The socio-technical and economic perspectives, Applied Energy 155 (2015), 131–149.

[13] V. Kabakian, M.C. McManus, H. Harajli, Attributional life cycle assessment of mounted 1.8 kWp monocrystalline photovoltaic system with batteries and comparison with fossil energy production system, Applied Energy 154 (2015), 428–437.

[14] R. López-Luque, J. Reca, J. Martínez, Optimal design of a standalone direct pumping photovoltaic system for deficit irrigation of olive orchards, Applied Energy 149 (2015), 13–23.

[15] R.Sarrias, L.M. Fernández, C.A. García, F.Jurado, Coordinate operation of power sources in a doubly-fed induction generator wind turbine/battery hybrid power system, Journal of Power Sources 205 (2012), 354–366,

[16] B.Bhandari, K.T.Lee, C.S.Lee, C.K.Song, R.K.Maskey, S.H.Ahn, A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources, Applied Energy 133 (2014), 236–242.

[17] M. J. Lavorante, L.G. Messina, J.I. Franco, P. Bonelli, Design of an integrated power system using a proton exchange membrane fuel cell, International Journal of Hydrogen Energy 39 (2014), 8631 -8634.

[18] P. Rizzi, E. Pinatel, C. Luetto, P. Florian, A. Graizzaro, S. Gagliano, M. Baricco, Integration of a PEM fuel cell with a metal hydride tank for stationary applications, Journal of alloys and compounds 645 (2015), 338–342.

[19] Z.Ural, M.T.Gencoglu, Design and simulation of a solar-hydrogen system for different situations, International journal of hydrogen energy 39 (2014), 8833 – 8840.

[20] O. Ulleberg, T.Nakken, A.Ete, The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools, International journal of hydrogen energy 35 (2010), 1841–1852.

[21] MJ.J. Khan, M.T. Iqbal, Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland, Renewable Energy, 30 (2005), 835-854.

[22] C. Wang, M.H. Nehrir, Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System, IEEE Transactions on Energy Conversion 23 (2008), 957-967.

[23] S.B. Silva, M.M. Severino, M.A.G. de Oliveira, A stand-alone hybrid photovoltaic, fuel cell and battery system: A case study of Tocantins, Brazil, Renewable Energy 57 (2013), 384-389.

[24] P. Balcombe, D. Rigby, A. Azapagic, Energy self-sufficiency, grid demand variability and consumer costs: Integrating solar PV, Stirling engine CHP and battery storage, Applied Energy 155 (2015), 393–408.

[25] P. Balcombe, D. Rigby, A. Azapagic, Environmental impacts of microgeneration: Integrating solar PV, Stirling engine CHP and battery storage, Applied Energy 139 (2015), 245–259.

[26] I. Staffel, Zero carbon infinite COP heat from fuel cell CHP, Applied Energy 147 (2015), 373–385.

[27] C. Koroneos, A. Dompros, G. Roumbas, N. Moussiopoulos, "Life cycle assessment of hydrogen fuel production processes", International Journal of Hydrogen Energy, 29 (2004), 1443 – 1450.

[28] R. Bhandari, C.A. Trudewind, P.Zapp, Life cycle assessment of hydrogen production via electrolysis - a review, Journal of cleaner production 85 (2014), 151-163.
[29] J. Kim, T. Kim, Compact PEM fuel cell system combined with all-in-one hydrogen generator using chemical hydride as a hydrogen source, Applied Energy 160 (2015), 945–953.
[30] F.I. Khan, K. Hawboldt, M.T. Iqbal, Life Cycle Analysis of wind–fuel cell integrated system, Renewable Energy 30 (2005), 157-177.
[31] http://dati.istat.it/Index.aspx?DataSetCode=DCCV_CNSENRG
[32] http://www.autorita.energia.it/it/com_stampa/08/080902.htm
[33] JRC, E.C., Climate-SAF PVGIS Database, in http://re.jrc.ec.europa.eu/pvgis/apps3/pvest.php
[34] V. Girgenti, C. Peano, C. Baudino, N. Tecco, From "farm to fork" strawberry system: Current realities and potential innovative scenarios from life cycle assessment of non-renewable energy use and greenhouse gas emissions, Science of the Total Environment 473 – 474 (2014), 48 – 53.
[35] V. Girgenti, C. Peano, M. Bounous, C. Baudino, A life cycle assesment of non-renewable energy use and greenhouse gas emissions associated with blueberry and raspberry production in northern Italy, Science of the Total Environment 458-460 (2013), 414 – 418.
[36] M. Pehnt, Life-cycle assessment of fuel cell stacks. International Journal of Hydrogen Energy 26 (2001), 91-101.
[37] SIMA PRO 8.1, LCA software, in http://www.pre.nl/simapro/simapro_lca_software.htm
[38] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, R. Rosenbaum, IMPACT 2002+: a new life cycle impact assessment methodology, The International Journal of Life Cycle Assessment 8 (2003), 324-330.
[39] ISO, E., 14040: 2006. Environmental management–Life cycle assessment–Principles and framework, 2006.
[40] Manual, F.-H., Guidance document for performing LCAs on fuel cell technologies and hydrogen technologies, in http://www.fc-hyguide.eu/. 2011.
[41] Ecoinvent 2010 Database, in http://www.ecoinvent.ch/
[45] B. Sorensen, Total life-cycle assessment of PEM fuel cell car, Paper 3-1189 in Proc. 15th World Hydrogen Energy Conf., Yokohama. CDROM, World Hydrogen Energy Association. 2004.
[46] N. Jungbluth, M. Tuchschmid, Photovoltaics, Ecoinvent report n° 6-XII (2007), Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
[47] M. Carmo, D.L. Fritz, J. Mergel, D. Stolten, A comprehensive review on PEM water electrolysis, International Journal of Hydrogen Energy 38 (2013), 4901-4934.
[48] E. Cetinkaya, I. Dincer, G.F. Naterer, Life cycle assessment of various hydrogen production methods, International Journal of Hydrogen Energy 37 (2012), 2071 – 2080.

[49] P. L. Spath, M. K. Mann, Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis, Lawrence Livermore National Laboratory, February 2014, NREL/MP-560-35404, available at: http://www.nrel.gov/docs/fy04osti/35404.pdf.

[50] D. A. Notter, M. Gauch, R. Widmer, P. W. Ager, A. Stamp, R. Zah, H.-J. Althaus, contribution of li-ion batteries to the environmental impact of electric vehicles, Environmental Science & Technology 44 (2010), 6550–6556.

[51] J.B. Dunn, L. Gaines, J. Sullivan, M.Q. Wang, Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. Environmental Science & Technology 46 (2012), 12704-12710.

[52] S. Amarakoon, J. Smith, and B. Segal, Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles, final report, 2013.