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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.



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 (electrolyzer 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

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

2

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9

10 **Abstract**

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

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

27

28 **Keywords**

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

30

31 **1. Introduction**

32 In the last decades, energy related problems are becoming more stringent and there is an increased
33 interest in renewable energy production methods [1-3]. One of the main problems of renewable
34 resources is that they are subjected to variations in the production according to the hour of the day,
35 the period of the year, etc. Therefore, it is necessary to store produced energy allowing its use after

1 production. Energy storage has many attractive functions, such as: (i) helping in meeting peak
2 electrical load demands, (ii) providing time varying energy management, (iii) alleviating the
3 intermittence of renewable source power generation, (iv) improving power quality/reliability, (v)
4 meeting remote and vehicle load needs, (vi) supporting the realization of smart grids, (vii) helping
5 with the management of distributed/standby power generation, (viii) reducing electrical energy
6 import during peak demand periods [4].

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

16 A good storage system should be useful also if the system is located in a remote off grid area, like
17 mountain lodges or small islands. In the case of the former, in fact, according to two studies in alpine
18 regions of Italy (Valle d'Aosta and Friuli Venezia Giulia), around 60% of mountain lodges are not
19 grid-connected. In Valle d'Aosta, 54% of the lodges use diesel generation systems to produce all or
20 at least part of the electricity needed (28% for example use diesel generation combined with
21 photovoltaic panels) [7] and in Friuli Venezia Giulia 58% of lodges are not grid connected, of which
22 42% using diesel generation systems [8]. On the other hand, in Italy there are 12 small islands that
23 are not grid connected and, still nowadays, are producing the greatest part of the electricity needed
24 with diesel generation systems. Since the latter are not efficient and the lorries transporting the fuel
25 can only be carried on special ships, this way of generating electricity is expensive and polluting [9],
26 with poor power quality performance and high maintenance costs. The problem is worsened by the
27 legislation and administrative barriers that obstacle the diffusion of renewable energy production
28 technologies. This is not only the case of Italian islands, but also that of many others spread all over
29 the world [10]. Therefore, for the development of remote regions, various integrated power systems
30 were suggested in the last few years in the literature. In various studies, photovoltaic panels or wind
31 turbines are combined with batteries to store energy and provide it to several households, but they
32 can be used also for irrigation systems, such as for olive orchards irrigation [11-16].

33 Other studies are related to the use of fuel cell-based systems, i.e. systems composed by fuel cell
34 (FC), electrolyzer and hydrogen tank, that can be used for energy storage [17,18]. These hydrogen-
35 based storage systems are sometimes coupled with renewable energy sources, such as wind turbines

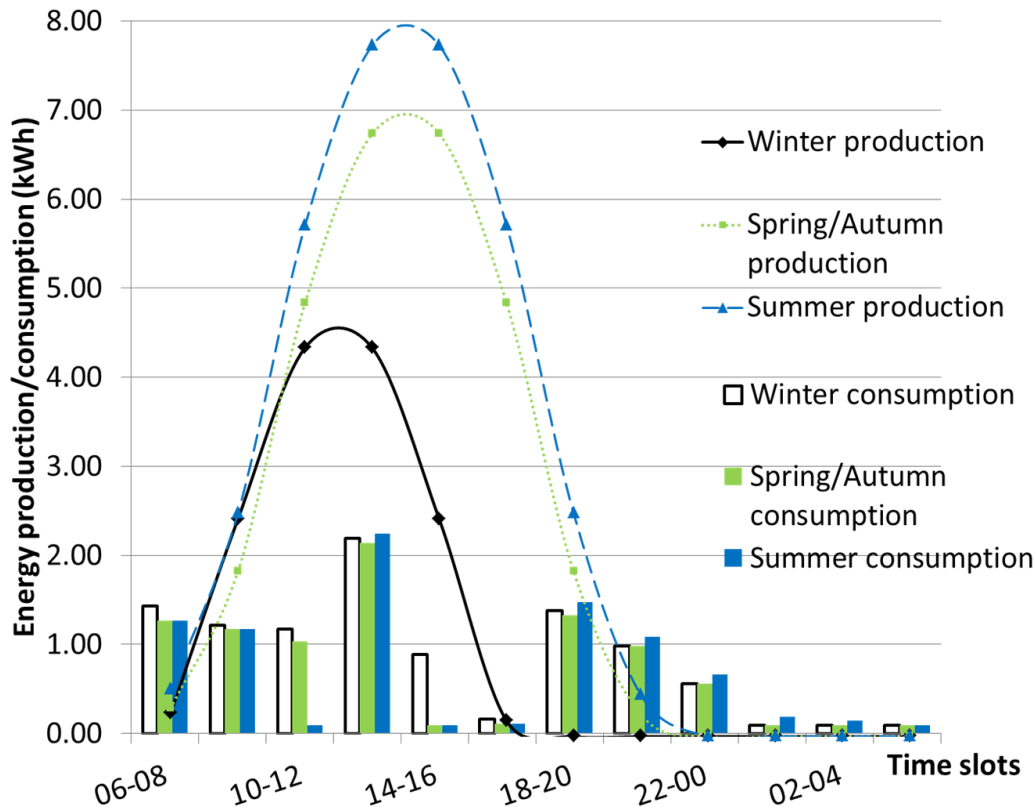
1 or photovoltaic panels, that are mainly used to provide energy to the electrolyzer [19-23]. In some
2 cases a comparison of the storage energy systems used (i.e. FC and batteries) are made [23].
3 Different integrated systems are described: in [18] the study was devoted to the integration of a
4 hydride tank, where $\text{LaNi}_{4.8}\text{Al}_{0.2}$ was used to store H_2 , with a PEM-FC; this systems gives 6h
5 autonomy delivering a total energy of 4.8 kWh. In the island of Utsira in Norway [20] a
6 wind/hydrogen energy system was installed, composed by wind turbine, electrolyzer, hydrogen
7 storage in form of pressured gas and a PEM-FC. The system gives 2–3 days of full energy autonomy
8 for 10 households on the island. Lavorante et al. [17] proposed an integrated power system for
9 remote communities, composed by electrolyzers, cylinders tanks and PEM-FC. The system has an
10 autonomy of 16h and a power of 53 kW. In a pre-feasibility study of stand-alone hybrid energy
11 systems for applications in Newfoundland [21], a comparison of various renewable and non-
12 renewable energy sources and energy storage methods was presented, for a remote house having an
13 energy consumption of 25 kWh per day with a 4.73 kW peak power demand. It was found that, even
14 if a wind–diesel–battery system is the most suitable solution at present, a wind–fuel cell system
15 would become a superior choice with a reduction of fuel cell cost to 15% of its current value.
16 Silva et al. [23] described a pilot-project set up in an environmental protection area, in Brazil,
17 focusing the study on technical and cost issues. As in the [21] study, it was found that fuel cell and
18 electrolyzer are costly and the best option, from the cost point of view, for storing energy from
19 photovoltaic systems is still the use of batteries.
20 The use of fuel cells is also a valid solution for combined heat and power generation (CHP) [24 - 26].
21 The environmental impact and energy consumption of a power system can be adequately evaluated
22 by performing a Life Cycle Assessment analysis (LCA), a method that takes into account the
23 environmental impact of a product or a process over its full life cycle (from “cradle to grave”).
24 Different examples are reported in literature in which various H_2 production methods are compared
25 [1, 27-29].
26 In this work, two alternative integrated power systems will be taken into account and compared: one
27 based on photovoltaics and hydrogen technology, the other based on photovoltaic and batteries. The
28 two systems will be compared from a technical and economical point of view and a preliminary Life
29 Cycle Assessment analysis (LCA) will be performed, in order to evaluate the environmental impact
30 of the systems, finding out which components are more critical from this point of view. It is the first
31 study of this kind for the area of Turin. Most studies are limited to the system’s sizing [10,11,14-
32 19,22,26] and some of them consider also cost analysis [12,20,21,23,24]. LCA is instead considered
33 only in very few studies [13,25,30] and among these, only that of Balcombe et al. [24,25], considers
34 all the three aspects of the CHP system. The present study aims to take into account system’s sizing,
35 LCA and cost analysis together for the first time for the selected systems.

1 **2. Possible application**

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

7 **2.1 Power load curves and average electricity consumption of a family**

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



1

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

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

19 From loads curves, the average daily consumption of a family of 3-4 members was determined to be
 20 10.25 kWh in winter, 8.96 kWh in spring and autumn and 8.62 kWh in summer. These data can be

1 compared with those provided by statistic studies, which give not differentiate results for seasons and
2 that sometimes are very different one from another. These can in fact depend on the part of Italy they
3 are referred to: considering, for example, the electricity consumption for domestic use for Italian
4 provincial capitals provided by ISTAT (warehouse of statistics currently produced by the Italian
5 National Institute of Statistics) in 2012, the highest daily consumption of electricity was registered in
6 Olbia (17.56 kWh) and the lowest in Trento (9.80 kWh), while in industrial cities like Milan and
7 Turin the electrical consumption was 11.24 kWh and 12.44 kWh, respectively [31].
8 On the other hand, a study by the Italian Regulatory Authority for Electricity Gas and Water reports
9 the value 7.40 kWh/day, which represents an average on family consumptions of electricity in Italy
10 [32]. The difference between these values is due to the sometimes big differences among families
11 living in different parts of Italy, due to climate, habits and number of electrical appliances.
12 The values calculated from load curves are in agreement with data reported in literature, therefore, an
13 average value of 10.25 kWh/day was choose to size the systems.
14 To build a well-functioning system it is not only necessary to know the total amount of electricity
15 needed in a day, but also the sizes of the peaks of consumption. Therefore, considering the load
16 curves, the system was sized for providing 3 kW load, which is also the most common power for
17 electricity supply for Italian families.

18 **2.2 Irradiation data**

19 The solar resource was considered for the area of Turin. The irradiation data taken from the online
20 database by JRC [33] show that the annual average solar radiation is 4.80 kWh/m²/day for Turin,
21 which is an encouraging value for electricity production from photovoltaics.
22 To define the correct sizing of the system, however, it is necessary to consider also seasonal
23 fluctuations: the monthly average irradiation data, taken from the database by JRC [33], are shown in
24 Fig.2. The difference between the irradiation values of summer and winter (6.59 and 2.79 kWh/m²/d
25 for July and December, respectively) is significant: for the right sizing of the system the worst
26 conditions have to be kept in mind, i.e. the winter months, in particular December.
27 Thus the system was sized basing on the average daily irradiation data of December. For comparison,
28 however, the irradiation data of July and April were considered as well, as examples of summer and
29 spring irradiation, respectively. The irradiation data of April are quite similar to that of September, as
30 can be seen in Fig. 2.



1

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

4 **3. System description**

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

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

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

12 Self-sufficiency of the system: 2 days;

13 Maximum power load: 3 kW at 220 Vac;

14 Load curve for winter months (Fig. 1);

15 Technical data for a single photovoltaic panel: power 250 W each; voltage 30.2 Vdc; current 8.2 A;
 16 surface area 1.65 m²; efficiency 15.2%.

17 **3.1 Sizing of the system with battery storage**

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

22 **3.1.1 Sizing of the photovoltaic array**

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

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

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

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

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

- 16 i) 3 strings connected parallel, each composed by 4 panels connected series, providing a 120 Vdc, 24
17 A current;
18 ii) 2 strings connected in parallel, each composed by 4 panels in series, providing a 120 Vdc, 16 A
19 current.

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

22 **3.1.2 Sizing of the battery storage**

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

26 Since a 48 Vdc inverter is chosen, the final system is composed by 12 batteries, supplying 48 Vdc at
27 450 Ah.

28 In Fig. 3 a detailed representation of the described system is shown in the highlighted area. The
29 detailed list of its components is: 20 Polycrystalline silicon solar panels with nominal power output
30 of 250 W each, connected in series in strings (4 panels per string); the strings are grouped by 2 and 3
31 in parallel; 2 solar controllers, each one connected to a series of panel strings; 12 Lithium batteries
32 (LiFePO_4) with power output of 12 Vdc 150 Ah each; a 3 kW inverter converting the 48 Vdc from
33 the battery pack or the photovoltaic panels in 220 Vac required by the load.

34 **3.2 Sizing of the fuel cell-based system**

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

3 1) Technical data of the electrolyzer

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

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

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

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

11 **3.2.1 Sizing of the photovoltaic array**

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

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

19 Since the electrolyzer requires 5 kWh to produce 1000 l of hydrogen, the energy needed to produce
20 3300 l is given by:

$$21 \quad (3300 \text{ l} * 5 \text{ kWh}) / 1000 \text{ l} = 16.5 \text{ kWh}$$

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

$$25 \quad \text{Total energy request (kWh)} = (10.25 - 4.5) + 16.5 = 22.25 \text{ kWh}$$

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

29 To supply the right voltage to the charge controller, the following configuration is adopted: 3 strings
30 connected parallel, each composed by 4 panels connected series, providing a 120 Vdc 24 A current;
31 3 strings connected parallel, each composed by 4 panels connected series, providing a 120 Vdc 24 A
32 current; 2 strings connected in parallel, each composed by 4 panels in series, providing a 120 Vdc 16
33 A current.

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

3 **3.2.2 Sizing of the hydrogen storage**

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

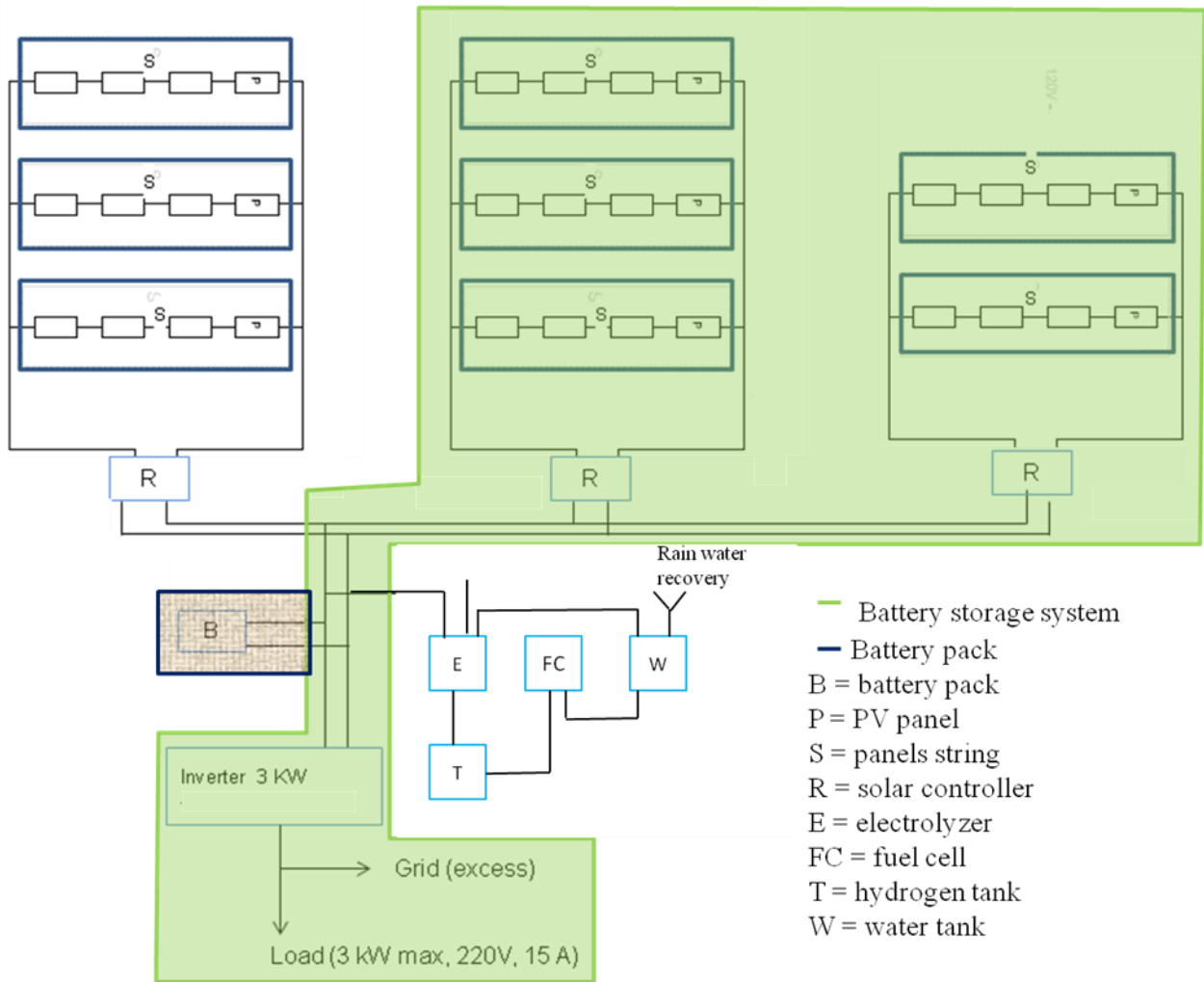
6 Using standard cylinders for gas compressed at 30 bar (pressure of H₂ produced by the electrolyzer)
7 with an internal volume of 50 l, the total number of cylinders needed is 10. Since standard cylinder
8 bundles are composed by 12 tanks, 2 additional cylinders are added to the system.

9 In Fig. 3 a detailed representation of the system described is shown: the structure is the same as that
10 of the other system (in the highlighted area), with some additional components. The detailed list of
11 components is: 32 polycrystalline silicon solar panels with nominal power output of 250 W,
12 connected in series in strings (4 panels per string); the strings are grouped by 2 and 3 in parallel; 3
13 solar controllers, each one connected to a series of panel strings; 4 LiFePO₄ batteries with power
14 output of 12 Vdc 75 Ah each; a 3 kW inverter converting the 48 Vdc from the battery pack or the
15 photovoltaic panels in 220 Vac required by the load; 12 type II gas tanks with a capacity of 50 l each,
16 made aluminium alloys; a 5 kW alkaline electrolyzer; a 3 kW PEM fuel cell; an 80 l water tank for
17 the electrolyzer. The latter is equipped with a rain water recovery system.

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

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

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



1
2 **Fig. 3** Scheme of the integrated systems: in the highlighted area the components of the system with battery storage are
3 visible. The system with hydrogen storage is composed of the components in the highlighted area, to which an additional
4 photovoltaic array and the electrolyzer+fuel cell device are added. The battery pack in the dark-framed area is used by
5 both systems, but with different size.

6 **4. Cost analysis**

7 Knowing the correct size of the systems, it is possible to estimate costs of the components, in order
8 to establish which system is more competitive from an economical point of view. The costs of the
9 commercial devices supposed to be used in the construction of the two systems of Fig. 3 are listed in
10 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		

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

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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;

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

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

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

10 **5.1 Goal and scope definition**

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

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

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

20 **5.2 System Boundary**

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

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

28 **5.3 Life Cycle Inventory (LCI)**

29 The system boundary defines the unit processes to be included in the system. A model of the product
30 system is conceived to represent the interaction of the product system with the environment. The
31 model is commonly programmed in a dedicated LCA software tool and covers each step of the life
32 cycle from the raw material extraction through to the products end of life in a series of
33 interconnected steps called processes. Interaction with the environment is represented as elementary

1 flows crossing the system boundary, e.g. resources taken from nature and introduced into the product
 2 system or emissions arising from combustion, physical, thermal or chemical conversion processes
 3 which are vented into the environment. The elementary flows which make up the interaction of a
 4 product system with the environment are compiled. This compilation is referred to as the Life Cycle
 5 Inventory (LCI) [40]. Due to the difficulty of finding data on the production of the different devices
 6 directly from manufacturers, they were taken from the Ecoinvent database [41]. Since on the latter it
 7 was not possible to find exactly the components of the systems studied, in some cases similar
 8 products were considered, while in other cases other approximations were made. In Tab. 3 the list of
 9 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 ₂ O 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
	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)

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

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

8 5.4 Impact assessment

9 The large number of resources and emissions that make up the LCI is translated into a handful of
 10 environmental impact categories in the Life Cycle Impact Assessment (LCIA) step. Mandatory
 11 elements in the LCIA are classification and characterization.

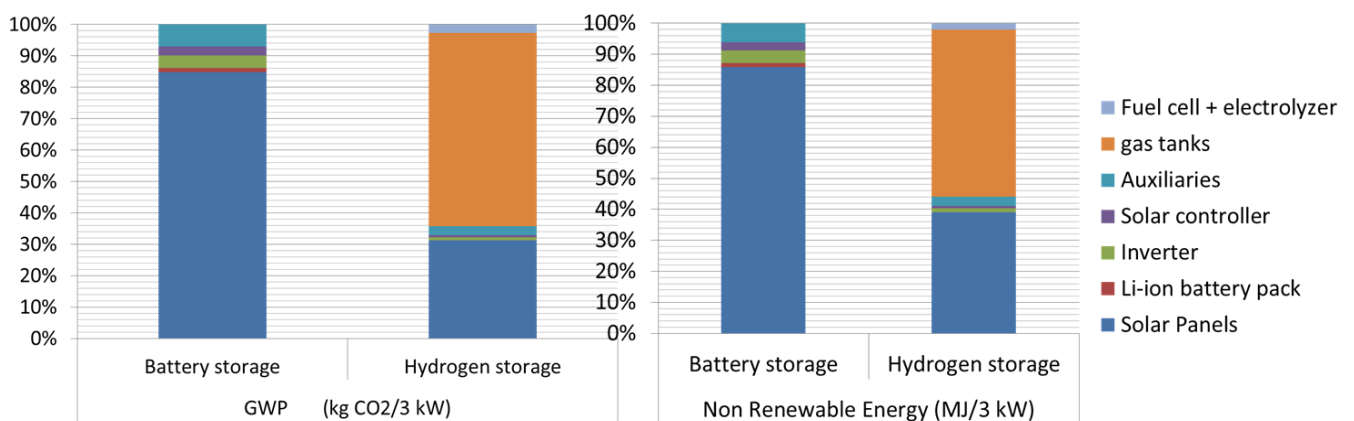
12 Classification is the assignment of the various emissions into impact categories. Most elementary
 13 flows can be assigned to one impact category, but in some cases a single attribution is not possible.
 14 In these cases, emissions are assigned to all impact categories they have impact on.

15 Characterization means the definition of how much impact an emission has with regard to a pre-
 16 defined reference substance of an impact category. This is expressed by means of a characterization
 17 factor [42].

18 For this study, the impact categories chosen are global warming potential (GWP) and Non
 19 Renewable Energy. These were evaluated using Impact 2002+ method [38].

20 5.5 LCA results and discussion

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



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

24 The solar panels have a significant impact on both systems, 81% and 30% GWP, 80% and 37%
 25 Non-Renewable Energy, respectively for the battery-based and for the fuel cell-based system.
 26 According to Jungbluth et al [43], the impact of a silicon-based solar panel is mainly due to the
 27

1 highly energy intensive purification process of silicon. The authors also point out that the PV sector
2 is growing rapidly together with the technology involved. It is thus possible that the high impact of
3 Si-based solar panels will be significantly reduced within few years thanks to production process
4 improvements.

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

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

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

19 It is thus possible that the impact of the alkaline electrolyzer is overrated with this approximation.
20 The low impact of an electrolyzer is confirmed in literature [45] for a system composed by a
21 photovoltaic system and an electrolyzer in which over a total CO₂-equivalent emission of 0.0139 g/s,
22 only 0.0007 g/s are due to the electrolyzer. Another LCA study on a wind power plant [46] which
23 considers manufacturing and operation of the system, electrolysis, hydrogen compression and
24 storage, shows that just 4% of the total energy equivalent and of the total CO₂-equivalent emission
25 are due to the electrolyzer. In a LCA by Khan et al. [30] on a wind-fuel cell system, the values of
26 GWP reported for the fuel cell are around 19.90 g CO₂/kWh and those of the electrolyzer are around
27 11.14 g CO₂/kWh over a total of 41.08 g CO₂/kWh for the integrated system. These values can
28 slightly change if different inventory data are used, referred to different power generation sources;
29 this variation in the GWP values highlights their sensitivity to power generation mix sources used for
30 the production of the integrated system and can explain the variability of results reported in
31 literature.

32 Also the batteries for the battery-based system have a small effect on the total impact for both
33 categories (1% for both). According to studies on LiMn₂O₄ batteries [47,48], the biggest contribution
34 to the impact comes from the cathode material, followed by the anode material. This impact can be
35 reduced improving manufacturing process, but also recycling of the materials at the end of the life of

1 the battery. This is confirmed by another study [49], which considers more Li-based chemistries: the
2 production of the cathode and anode materials represents a significant slice on the impact of the
3 whole battery, in particular because of the use of metals like chromium, cobalt and nickel. Another
4 important point, according to this study, is the use of steel and aluminium for the battery casing: the
5 authors recommend the reduction of the percent by mass of these components. Also the fuel cell-
6 based system needs batteries for start-up, these have been grouped into the “auxiliaries” because their
7 energy is used only for the fuel cell, and they do not contribute to the energy storage for the house.
8 The auxiliaries give a marginal contribution to the impact of the battery-based system (7% GWP and
9 6% Non-Renewable Energy) and to that of the fuel cell-based (3% on both indicators). The main
10 contributor to this impact is the hot dip galvanized steel used for the support structure, followed by
11 the cable, and in particular the amount of copper used for its production.

12 **6. Conclusions**

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

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

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