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Economic assessment of hydrogen production in a Renewable Energy Community in Italy

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ABSTRACT

Renewable Energy Community (REC) is a new paradigm in European Union to produce, transform, share and sell renewables at a local consumer level, also via e-fuel (i.e. hydrogen). This work investigates the economic feasibility of a hydrogen Power-to-Gas (PtG) system realized inside a REC, using only excess renewable electricity, not consumed by REC itself. A single centralized photovoltaic (PV) plant is directly connected to an electrolyser; a hydrogen compressor and two hydrogen storages at low and high pressure complete the PtG system. A scenario of a REC composed by 450 residential electric users (around 1,000 people) has been analysed, coupled with described PtG considering eight different sizes of PV plant. In the study, Italian subsidies to REC shared energy are evaluated as incentives to hydrogen production. An optimal size of PtG components for each PV size is investigated at the limit of economical sustainability, evaluating net present value (NPV) positive and near zero. Results show that for the considered REC, it is possible to produce and sell up to around 3 tons per year of green hydrogen at most to the same lowest selling price declared currently in the Italian market (5 €/kg).

1. Introduction

Global issues regarding climate change are at the top of international priorities. With the Paris Agreement, 195 countries adopted the first universal and legally binding covenant on the global climate, defining a global action plan aimed at keeping global warming well below +2 °C compared to the pre-industrial era [1]. Europe has set carbon-neutrality goal by 2050 [2]. The Intergovernmental Panel on Climate Change clearly states that it is urgent to limit global warming to +1.5 °C rather than +2 °C [3]. The Glasgow COP26 confirmed the +1.5 °C threshold, and the final outlook states that commitments must be urgently transformed into tangible action [4]. Sharm el-Sheikh COP27 confirms COP26 previous conclusions, highlighting multi trillions needs per year to reach net zero emissions by 2050 [5].

Generation of renewable energy, both with large power plants and with small systems near the consumers, constitutes a crucial factor in curbing global warming.

1.1. Renewable energy community EU framework

The European Directive on Renewable Energy (RED II) [6] described Renewable Energy Communities (so called RECs) as a new legal entity for small scale decarbonisation both for residential end-users and SMEs [7–10]. In Italy the RED II Directive was adopted in November 2021 [11] and the full operative legislative framework should be completed by first quarter of 2023 with pronouncements of GSE (Gestore dei Servizi Energetici) and ARERA (Autorità di Regolazione per Energia, Reti e Ambiente). GSE is the Italian government-owned enterprise that promotes and incentives production of electricity from renewable sources and energy efficiency. ARERA is the Italian authority for regulation of markets based on a network.

A Renewable Energy Community is a legal entity as stated in article 2 paragraph (16) of RED II [6]. REC "in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity". The primary purpose of REC is "to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits".

Members of a REC are producers, consumers or prosumers (both producers and consumers) of renewable energy, and their role will be

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strategic in renewable evolution [12]. Article 8 of the reference Italian law [11] legally defined the concept of "shared energy", which is the energy produced by renewables and consumed in the same hour by users within a REC. Furthermore in detail as defined in article 2, paragraph 1), letter q) of Dlgs 199/2021 [11], shared energy "is equal to the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable source plants and the electricity withdrawn by all the associated end-customers located in the same market area". Shared energy receives economic subsidies by Italian Government.

1.2. Power-to-gas for a local use of renewables

A REC produces, consumes, stores and sells renewable energy also via e-fuel (i.e., hydrogen). Hydrogen is currently used as a feedstock or energy carrier in different industrial sectors, and it will be used in many new applications during next year like logistics and transportation. These new applications will start a different local market for renewables [13]. Production of green hydrogen is a key factor for decarbonization processes, as well as its sale price equal or lower to fossil hydrogen.

1.3. Literature review

The integration of a hydrogen Power-to-Gas (PtG) in a based on European Union (EU) framework REC appears not yet widely investigated. Pastore et al. [14] first introduced the concept to use REC incentives to support hydrogen production in decentralised energy systems. Bartolini et al. [15] investigated a REC with a high PV penetration and its management by different storage technologies including also a hydrogen PtG system. Uyar and Besikci [16] assessed the integration of hydrogen to obtain a 100% renewable energy communities. Instead, maximization of renewable consumption inside the local installation area has widely investigated. Luthander et al. [17] made a review of strategies to increase residential PV self-consumption. Frieden et al. [18] described schemes in different EU States to stimulate renewable local consumption and minimise the local renewable excess. Gallego-Castillo et al. [19] described different ways to increase renewable consumption in Spanish REC framework. Fischer and Madani [20] have revised role for heat pump for domestic heating to increase local renewable consumption. Todeschi et al. [21] described a methodology to plan REC in urban scenarios. Alvaro-Hermana et al. [22] stated an optimisation model to increase local consumption in a REC. De Santi et al. [23] presented an optimization algorithm to size a REC.

Also hydrogen small-scale PtG system in decentralized energy systems is well described in the recent year. Ghenai et al. [24] have optimised a system for a community in a desert area. Marino et al. [25] optimized a stand-alone PV system by hydrogen storage and fuel cell. Fonseca et al. [26] reviewed state of the art of hydrogen implementation in distributed energy system. A PtG in an Italian incentivized REC with a local storage and tecno-economic assessment as described following appears not completely described in literature.

1.4. Scope of the work

Integration of a hydrogen Power-to-Gas in a Renewable Energy Community is dealed in this work. This study aims to assess economic competitiveness of hydrogen production in a REC by a PtG scheme, in the current Italian hydrogen market. More in detail the main objective of the study is to investigate the condition to produce renewable hydrogen inside a REC, obtaining a hydrogen selling price lower or equal to the minimum one found in current Italian market. The purpose is achieved using economic subsidies to shared energy in a REC to decrease hydrogen selling price: REC subsidies are used as incentives to hydrogen production. Even if this idea is already presented in Pastore et al. [14], that appears as the only known work in the state of the art on hydrogen production in a REC under EU framework, novelty in this study is based on a different and explicit layout of the REC and of the PtG system. In fact, an electric interconnection scheme for the main components is defined in the study, such as a description of a hydrogen storage and delivering system. An assessment of the mass of hydrogen that can be produced in each case is presented. A calculation of the energy flows and of the impact of the components on Levelized cost of hydrogen (LCOH) and on Net present value (NPV) are presented. Lastly an optimal sizing of the technical components is investigated, within the possible renewable power range allowed for a single plant in a REC in Italy, to define economic sustainability limit of proposed scheme.

2. Material and methods

In this study, for electric residential users grouped in a REC, renewable generation is assured by a single centralized photovoltaic (PV) plant. An electrolyser is directly connected to the PV and uses exclusively energy from the PV (not from the grid). The energy converted into hydrogen is the excess one, not consumed in each hour of production by REC or by compression for hydrogen storage. The REC architecture is based solely on consumer members.

As a typical site, a village in a rural or remote area is considered, particularly in Central and the South of Italy: a study from ISTAT (the Italian Institute for Statistics) states that in those zones there are around 3,500 villages with a population under 2,000 inhabitants [27]. PV potential production in those areas is the best in Italy [28].

Handwerker et al. [29] stated that domestic production of hydrogen is not sustainable. To produce and sell renewable hydrogen by electrolysis in a PtG scheme, the best solution could be to install a centralised electrolyser connected directly to PV, with a storage.

A direct electrical connection of the electrolyser with the centralized PV plant avoids to buy electricity by the grid, preventing higher cost for hydrogen production.

The electrolyser market is pushing the Original Equipment Manufacturers (OEMs) in the sector towards bigger solution [30]: at least a 100 kW class for the electrolyser is suggested. Based on CEI 0-16 Italian standard, when operating an electric machine with a higher power than 100 kW, it is mandatory to use medium voltage (MV) connection. In Italy the maximum incentivized power for renewables in a REC is 1 MW per each renewable plant [11]. This is the domain for the analysis in this paper. In this domain the analysed scenario is composed by a single centralised PV system, matched with a REC composed only by consumer members, with a local hydrogen storage system. Different cases are evaluated varying only the size of the components and not the layout of the system.

2.1. REC composition and characterization

It is a supposed community of 944 people, grouped in 450 electric users, each of them composed by one to maximum four people with a share like in Table 1.

The distribution of the classes is based on Italian demographic characterization carried out in 2020 [31]. Each user is a low voltage (LV) passive consumer: no power generation at the users' level is considered.

Energy consumed in the REC is estimated for each hour of the year. To define the hourly energy consumption during a whole year (8,760 h),

Table 1
REC composition in the study.

members in each electric user	*distribution of the classes in the REC [%]*	*users in the REC*	*people per class*
1	35%	158	158
2	30%	135	270
3	25%	112	336
4	10%	45	180
total	*100%*	*450*	*944*

each user is characterized by an energy hourly consumption, based on three independent factors: type of users (considering energy consumption behaviour in each hour of the day), numbers of members in the user (from 1 to 4), seasonal aspects (considering life style and building management).

Capozzoli et al. [32] defined three daily energy user Consumption Behaviour $CB(t)$ (in blue line in Fig. 1) as percentages of daily electric total consumption estimated in each hour of the day. The sum of the percentages of energy consumption distribution over 24 h is therefore equal to 100% of daily consumption. For each hour is defined also a standard deviation to describe the stochastic daily variation of hourly consumption behaviour. A fourth profile is defined for a single member user, that usually doesn't stay at home during the working-hours of a day. The first three profiles (named type A, B, C), are suitable for all users (from 1 to 4 members), whereas profiles type D is used only for single member user.

Capozzoli et al. [32] stated also the electric energy annual consumption for different users. Mean daily consumption with an associated standard deviation has been inferred for each user, as a function of number of members (shown in Table 2).

Table 2
Electric energy daily consumption for each user.

members in each electric user	*Mean daily consumption [kWh/day]*	*standard deviation [kWh/day]*
1	3.84	0.46
2	7.26	0.87
3	7.95	0.95
4	10.82	1.30

Throughout the year the user electric consumption is affected by seasonal effects due to the variation in conditioning of buildings, illumination and lifestyle. Falabretti et al. [33] deduced the seasonal trend in power consumption by Italian national aggregate electrical demand from the national grid. Using open data for hourly national consumption [34] in Italy in 2017, with a Fast Fourier Transform analysis (FFT) a seasonal variation trend in electric consumption is inferred. A two harmonic signal reconstruction (red line in Fig. 2) is able to describe the seasonal National fluctuation in hourly power consumption $C^{Nat}(t)$ where t are the hours of the year (from 1 to 8,760) and C_m^{Nat} is the Italian average hourly consumption in 2017

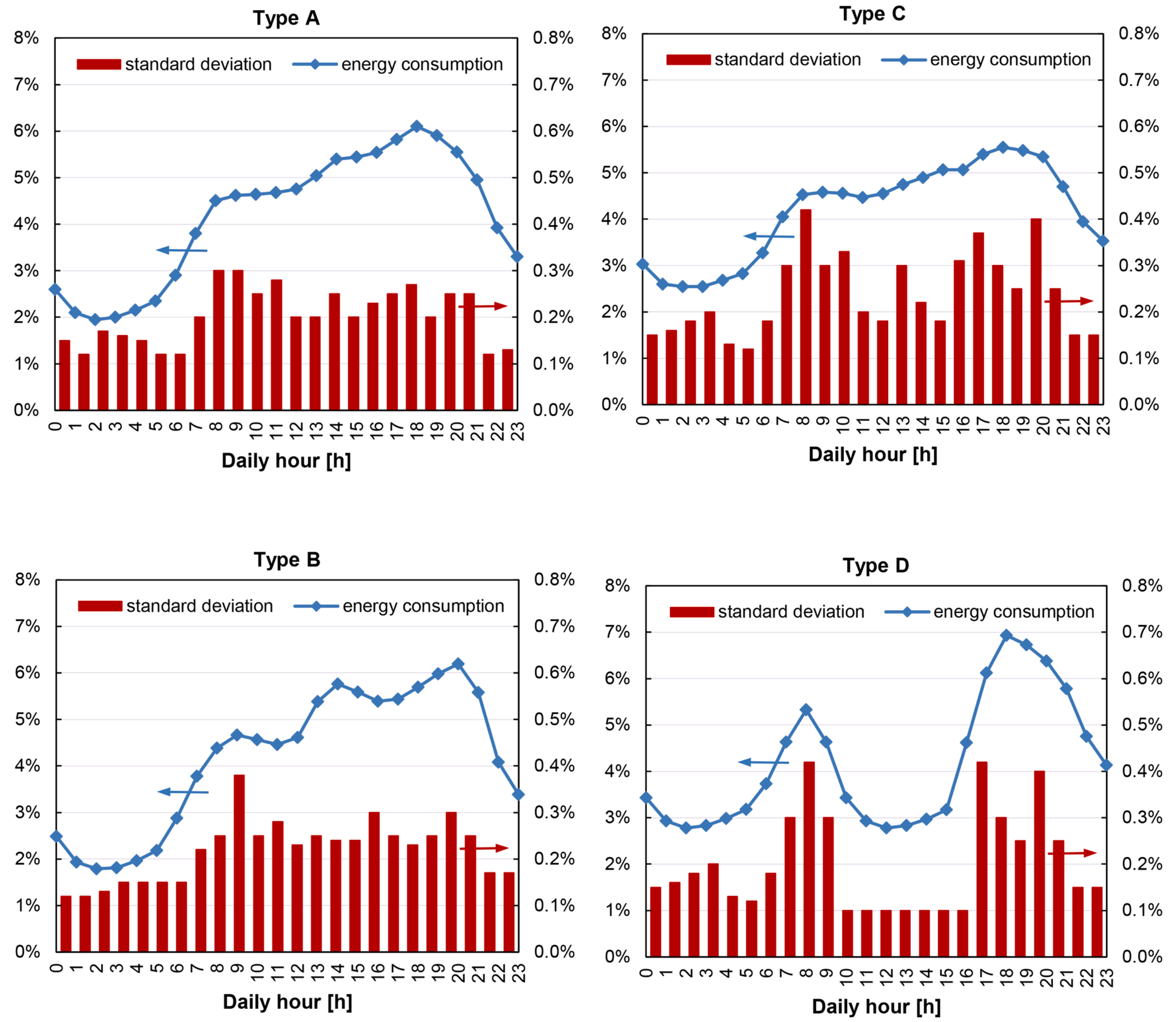

Fig. 1. Energy consumption behaviours of different type of users with standard deviation.

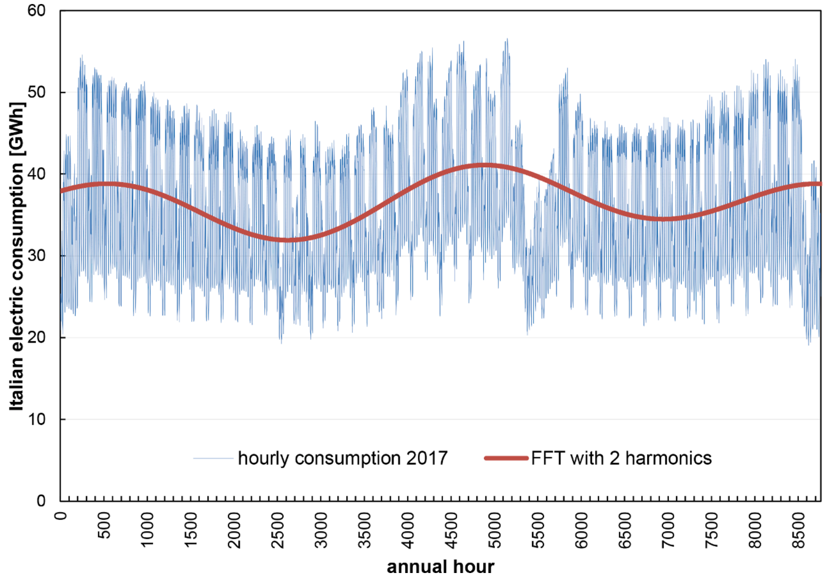

Fig. 2. Seasonal electric consumption variation in Italy during 2017.

$$C^{Nat}(t) = C^{Nat}_m [A_1 cos(\omega_1 t + \varphi_1) + A_2 cos(\omega_2 t + \varphi_2) + 1]$$

$$\begin{cases} C^{Nat}_m = 36579\ GWh \\ A_1 = 0.0472 \\ A_2 = 0.0910 \\ \omega_1 = 0.00077\ rad/h \\ \omega_1 = 0.00153\ rad/h \\ \varphi_1 = 1.780\ rad \\ \varphi_2 = -1.033\ rad \end{cases} \tag{2}$$

Such a variation is normalized around its mean value to create an hourly Seasonal Factor $SF(t)$.

$$SF(t) = A_1 cos(\omega_1 t + \varphi_1) + A_2 cos(\omega_2 t + \varphi_2) + 1 \tag{3}$$

The parameters of Eq. (3) have the same values indicated in Eq. (2).

For each user, an hourly energy consumption trend $C^{user}(t)$ during the year is calculable by mentioned factors: a daily Consumption Behaviour attributing a type from A to D ($CB(t)$), an Average Daily Consumption based on members numbers (ADC), and a Season Factor ($SF(t)$).

The electric daily consumption behaviour $CB(t)$ of each user is calculated starting from data described in Fig. 1 for four types of consumer (A, B, C and D). Each user maintains the same type during year. For each user of the REC, the percentage of consumption behaviour $CB(t)$ in each hour of a year is calculated as a random value in a Gaussian normal distribution that has mean value as indicated in correspondent hour of Fig. 1 (for the specific type) and correspondent standard deviation as indicated in the same Figure. Therefore, the hourly percentages of daily consumption behaviour are different for corresponding hours in the days during the year: $CB(t)$ has the same shape between days but a different value in each corresponding hour.

The average daily consumption (ADC) by each user is constant throughout the year, and it is calculated for each user as function of number of members (from 1 to 4) starting from value of mean value and standard deviation indicated in Table 2. For each user of the REC with a certain number of members, ADC is equal to a random value in the Gaussian normal distribution that has mean value as indicated in column 2 and standard deviation as indicated in column 3 of Table 2. The average daily consumption (ADC) of energy for each user is multiplied by that percentage of consumption behaviour $CB(t)$ defined above, to obtain the energy consumption value for each hour. Finally, the result is multiplied hourly by seasonal factor $SF(t)$, to create the ultimate trend of consumption for each user $C_{user}(t)$ in each hour during the year.

$$C_{user}(t) = CB(t) \cdot ADC \cdot SF(t) \tag{4}$$

An example of result of calculation of a user energy consumption $C^{user}(t)$ described above is shown in Figs. 3 and 4 for few hours and a whole year respectively. In the Figures a four members user is chosen with a power consumption daily distribution type A and an average daily consumption of $ADC = 11.66$ kWh/day (annually 4,269 kWh/year). Fig. 4 shows the seasonal trend.

Lastly the annual consumption distribution of the whole members of a REC is defined adding each hour consumption deduced with the described methodology for the 450 users of the REC, hour by hour during the year.

$$C_{REC}(t) = \sum_{i=1}^{450} C_{user}(t) \tag{5}$$

In the assumed model there is no resolution thicker than the hour: within the hour all the quantities are considered constant. In particular, the powers exchanged by the members of the REC during the hour are constant, and therefore hourly power and hourly energy coincide from a numerical point of view. A maximum hourly consumption of 192 kWh, means that the maximum power consumed by REC is 192 kW.

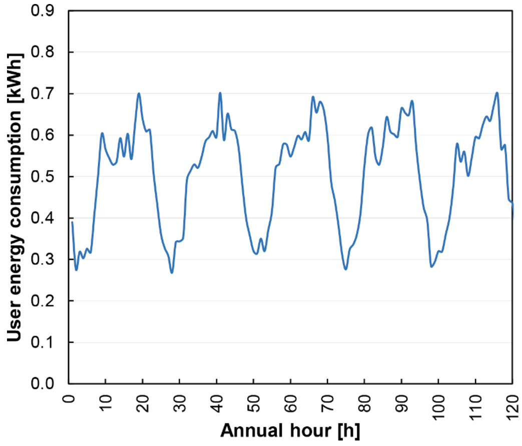

Fig. 3. Four members type A user hourly consumption.

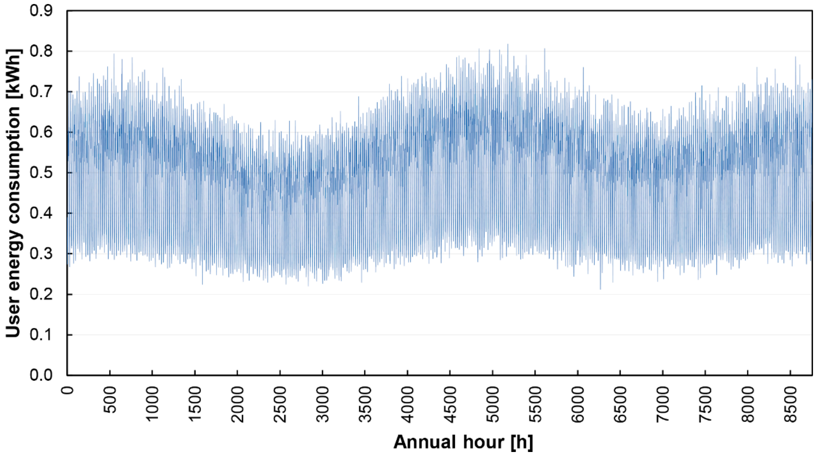

Fig. 4. Four members type A user hourly consumption in a year.

2.2. *Electric layout and flows*

In this study the power generation is provided by a PV plant [35] that serves final users grouped in REC configuration through Distribution System Operator (DSO) grid. No distributed power generation (i.e. PV on the roof of the users) will be considered.

The layout of the electrical system is shown schematically in Fig. 5.

In solid line low voltage (LV) grid and in dashed line medium voltage (MV) grid are represented. The black line is the private (REC) grid, whereas the red line is the DSO grid. A symbol of electric meter defines the point of delivery (POD) of each producer or consumer who constitute the REC.

A POD for the power generation is considered with a private single MV line interconnected with electric DSO grid. Energy produced by PV ($E_{PV}(t)$) is drawn first by REC as shared energy ($E_{se}(t)$) and then by compressor ($E_{comp}(t)$)

$$E_{se}(t) = \min\left(C_{REC}(t);\ E_{PV}(t) - E_{comp}(t)\right) \tag{6}$$

Eq. (6) is compliant with RED II and Italian reference law to define shared energy to estimate the subsidies to the REC. An electrolyser is connected to the FV line before POD to draw excess energy not used by compressor ($E_{Exc}(t)$) to produce hydrogen ($E_{Elect}(t)$) in the considered hour *t*. No energy from the grid is used to compress or produce hydrogen.

$$E_{Exc}(t) = \begin{cases} E_{PV}(t) - C_{REC}(t)\ if\ (E_{PV}(t) > C_{REC}(t)) \\ 0\ if\ (E_{PV}(t) \leq C_{REC}(t)) \end{cases} \tag{7}$$

$$E_{Elect}(t) = \begin{cases} \min\left(\mathrm{A}\dfrac{E_{Exc}(t) - E_{comp}(t)}{E_{core}}\mathrm{B}; n_{core}\right) \cdot E_{core}\ \ if\ E_{Exc}(t) \geq E_{comp}(t) \\ 0\ if\ E_{Exc}(t) < E_{comp}(t) \end{cases} \tag{8}$$

where n_{core} and E_{core} are number and power respectively of a single core in an electrolyser multicore as described below. A LV line from PV assures energy for compressor to store hydrogen at high pressure (200 bar) before selling.

If excess energy is not completely drawn by compressor or electrolyser, energy flows out of area ($E_{OOA}(t)$) where PV is installed and REC is connected throughout medium voltage DSO line (area described in Fig. 5):

$$E_{OOA}(t) = E_{Exc}(t) - E_{Elect}(t) - E_{Comp}(t) \tag{9}$$

If REC has not enough energy from PV, energy from outside area ($E_{FOA}(t)$) is used:

$$E_{FOA}(t) = \begin{cases} C_{REC}(t) - E_{FV}(t)\ if\ (E_{FV}(t) < C_{REC}(t)) \\ 0\ if\ (E_{FV}(t) \geq C_{REC}(t)) \end{cases} \tag{10}$$

2.3. *Power generation by photovoltaic plant*

Using data from JRC PVGIS initiative [28] a single kW peak PV system has been characterized in a Central Italy site ($E_{PV,\ 1kWp}(t)$) during each hour of a reference year (2017 at Latitude in decimal degrees: 41.9230; Longitude in decimal degrees: 14.6470). The orientation for PV is South and slope is 34° that is optimal value as assumed by PVGIS software. The hourly production takes into account meteorological and

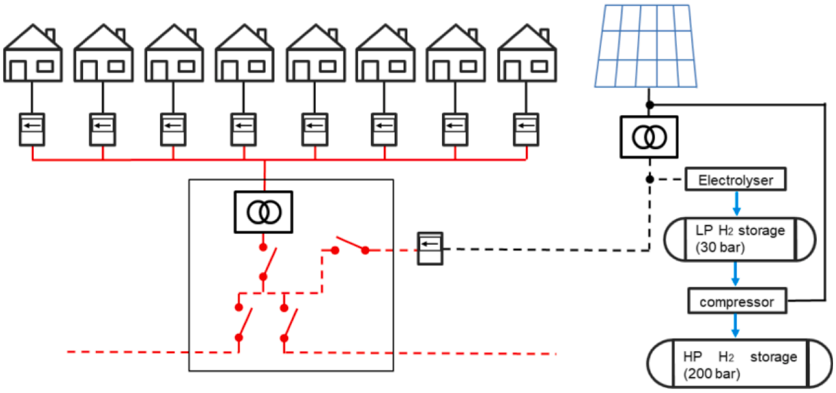

Fig. 5. Electric layout.

season effects of a typical year. The annual production is 1317 kWh/kWp.

The size of the PV power plant ($P_{p\ PV}$) in the study has been varied to define the more suitable solution. For each hypothesized size of the PV plant, an hourly distribution in a year of energy produced ($E_{PV}(t)$) by PV plant is evaluated based on same setting of JRC PVGIS (site, orientation, slope)

$$E_{PV}(t) = E_{PV,\ 1kWp}(t) \cdot P_{p\ PV} \tag{11}$$

2.4. Electrolyser

The electrolyser is a modular AEM type EL 2.1 from Enapter [36]. The inferred data are summarized in Table 3.

The electrolyser has a hydrogen output pressure up to 35 bar. A multicore electrolyser is assumed composed by independent cores (n_{core}), to better fit the power adsorbing of renewables not used in the REC or compressor hourly. Each core with auxiliary consumes an energy indicated by $E_{core} = 3.05\,kW$. Only on-off power mode is considered for each single core, with a simplified 0-100% duty cycle, without modulation of each core. The optimal number of cores is defined as output of the study, defining the total power input of electrolyser.

2.5. Storage of hydrogen

A low pressure (LP) 35 bar small hydrogen storage (cylinders) is put after the electrolyser that can be filled by a mass of hydrogen $Q_{Store\ LP}(t)$:

$$Q_{Store\ LP}(t) = Q_{Store\ LP}(t-1) + E_{Elet}(t) \cdot \eta_{Elect} / LHV_{H2} - Q_{H2\ trans}(t) \tag{12}$$

where η_{Elect} is efficiency indicated in Table 3 and LHV_{H2} is low heating value of hydrogen.

When a mass limit in LP storage ($Q_{H2\ LP\ lim}$) is reached, if there is enough excess of renewable, compressor draws energy ($E_{comp}(t)$) to transfer a mass of hydrogen ($Q_{H2\ trans}(t)$) to high pressure (HP) storage (200 bar).

$$E_{comp}(t) = \begin{cases} \min\left(P_{comp}; \dfrac{Q_{Store\ LP}(t-1)}{FROPR_{comp}}\right) \ if \ Q_{H2\ Trans}(t) > 0 \\ 0 \ if \ Q_{H2\ Trans}(t) = 0 \end{cases} \tag{13}$$

$$Q_{H2\ trans}(t) = \begin{cases} \min\left(Q_{H2\ Comp}; Q_{Store\ LP}(t-1)\right) \\ if \ Q_{Store\ LP}(t-1) \geq Q_{H2\ LP\ lim} \ AND \ E_{Exc}(t) \geq \min\left(P_{comp}; \dfrac{Q_{Store\ LP}(t-1)}{FROPR_{comp}}\right) \\ 0 \ if \ Q_{Store\ LP}(t-1) < Q_{H2\ LP\ lim} \ OR \ E_{Exc}(t) < \min\left(P_{comp}; \dfrac{Q_{Store\ LP}(t-1)}{FROPR_{comp}}\right) \end{cases}$$

where $FROPR_{comp}$ is flow rate on power ratio of the compressor and it is inferred by [37]. Mass capacity of the LP storage $Q_{H2\ LP\ C}$ is defined as result of the simulation as maximum value in the year of mass of hydrogen stored in LP $Q_{Store\ LP}(t)$.

Table 3
Single core characteristics of the electrolyser.

power consumption with auxiliary [kW]	*3.05*
power consumption to produce hydrogen [kW]	*2.4*
volumetric hydrogen flow rate [Nl/hour]	*508*
mass flow rate [g/hour]	*45.7*
efficiency [% LHV]	*49.9%*

$Q_{H2\ comp}$ is the mass flow rate of the compressor depending of its nominal power P_{comp}

$$Q_{H2\ comp} = P_{comp} \cdot FROPR_{comp} \tag{14}$$

$$FROPR_{comp} = \frac{flow\ rate}{motor\ rating} = \frac{126\ kg/h}{335\ kW} = 0.376\ \frac{kg/h}{kW} \tag{15}$$

Hydrogen mass in HP storage is $Q_{Store\ HP}(t)$

$$Q_{Store\ HP}(t) = Q_{Store\ HP}(t-1) + Q_{H2\ trans}(t) - Q_{Del}(t) \tag{16}$$

When the mass of hydrogen in HP is higher than a limit ($Q_{H2\ CC}$), hydrogen is delivered to customer ($Q_{Del}(t)$) for selling.

$$Q_{Del}(t) = \begin{cases} Q_{H2\ CC} \ if \ Q_{H2\ Store}(t-1) \geq Q_{H2\ CC} \\ 0 \ if \ Q_{H2\ Store}(t-1) < Q_{H2\ CC} \end{cases} \tag{17}$$

Size of HP storage (200 bar) is defined so that delivery to customer happen no more frequently than once every 48 h, to avoid a daily operation in the REC

$$Q_{Del}(t) \neq 0 \ if \ (\bar{\bar{t}} - \bar{t}) \geq 48h \tag{18}$$

where $\bar{t}$ and $\bar{\bar{t}}$ are two consecutive hours of delivery of hydrogen.

Three cylinder containers with a capacity of $Q_{Del}(t)$ composes the storage HP system (200 bar): one is at the customer, one at production site and one in travel or empty at the production site connected to the compressor, ready to be refill when the first one is full.

2.6. Economic facts

In a year simulation, cumulative values of shared energy, energy out of area, energy from outside area and hydrogen to the customer are calculated

$$E_{se\ ann} = \sum_{t=0}^{8760} E_{se}(t); \quad E_{OOA\ ann} = \sum_{t=0}^{8760} E_{OOA}(t); \tag{19}$$

$$E_{FOA\ ann} = \sum_{t=0}^{8760} E_{FOA}(t); \quad Q_{Del\ ann} = \sum_{t=0}^{8760} Q_{Del}(t) \tag{20}$$

Net present value (NPV) is considered as key factor for the economic analysis. Being that to have an economic benefit NPV has to be higher than zero, limit condition for feasibility can be considered as NPV equal to zero:

$$NPV = \sum_{a=0}^{n} \frac{E_{se\ ann} \cdot S_{se} + (E_{se\ a} + E_{OOA\ a}) \cdot PUN_a + Q_{Del\ a} \cdot P_{H2} - C_a - O\&M_a}{(1+d)^a} = 0 \tag{21}$$

where d is the interest rate, n lifetime of the investment, S_{se} is Italian economic subsidy for shared energy in a REC, PUN (Prezzo Unico Nazionale) is the wholesale electricity market price for Central Italy where the scenario is located, P_{H2} is minimum price of hydrogen in Italy [38]. Annual capital costs C_a and Operation and Maintenance costs $O\&$

Table 4
Economic parameters.

Parameter	*Value*	*Refs.*
Lifetime, n [year]	*20*	[40]
Interest rate, d	*5%*	[40]
PV capital cost [€/kW]	*1,250*	[41]
Electrolyser capital cost [€/kW]	*770*	[40,42]
Storage (250 bar) capital cost [€/kWh]	*13.5*	[37]
Compressor capital cost [€/kW] (<10 kW)	*6,700*	[37]
PV O&M cost [of CAPEX]	*1.2%*	[41]
Electrolyser O&M cost [€/kW year]	*19*	[40]
Storage O&M cost [of CAPEX]	*0.5%*	[41]
Compressor O&M cost [of CAPEX]	*4%*	[37]
Shared energy subsidies [€/kWh]	*0.119*	[43,44]
Electric price (South Italy 2020) [€/MWh]	*39*	[45]
Hydrogen selling price [€/kg]	*5*	[38]

M_a include PV, storages, compressor and electrolyser variable costs.

A Levelized Cost Of Hydrogen (LCOH) is evaluated for the various alternative cases, inspired by Levelized Cost Of Energy (LCOE) definition of Department for Business, Energy & Industrial Strategy [39].

$$LCOH=\sum_{a=0}^{n}\frac{C_a+O\&M_a-E_{se\,ann}\cdot S_{\mathrm{se}}-(E_{se\,ann}+E_{OOA\,ann})\cdot PUN_a}{(1+d)^a}\Bigg/\sum_{t=0}^{n}\frac{Q_{Del\,ann,a}}{(1+d)^a} \tag{22}$$

Values considered in the simulation are shown in Table 4. Exchange ratio between euro and dollar is consider equal to 1.

Schnuelle et al. [40] stated that electrolyser capital cost is around 770 €/kW; Collins [42] assumed that in 2025 Enapter will able to produce electrolyser at 550 €/kW. With a precautionary approach higher cost is considered in the simulation. Parks et al. [37] stated capital cost for compressor over 100 kW: a specific value can be inferred around 770 €/kW. During simulation appears that a size for compressor useful for the purpose is under 10 kW: interviews at Italian hydrogen compressor manufacturers at the beginning of 2021 indicates a specific capital cost of around 6,700 €/kW with a compressor power under 10 kW. This cautionary value is considered in the simulation. Electric selling price is evaluated as average value in 2020 to not take into account high price volatility due to market instability of 2021 and 2022: the chosen value is lower than current value (over 100 €/MWh in many day in last 2 years). It is a precautionary approach because higher value of electric selling price makes the investment more profitable and described cases most feasible.

Nicita et al. [38], based on Viesi et al. [46], stated that in Italy hydrogen selling price is in the range between 5.0 €/kg and 11.3 €/kg where the lower price refers to hydrogen produced in centralized plants by large scale steam fossil methane reformer (SMR), the higher to hydrogen produced on-site by electrolysis with grid electricity. Lower value is considered in the simulation to investigate if a hydrogen production in a REC can be competitive with fossil large scale production in Italy (worst-case).

3. Results and discussion

The REC's electric consumption as composed is characterized by a maximum hourly value of 192 kWh, a minimum value of 53 kWh, and an average value of 122 kWh. During a whole year the calculated energy consumption of the REC is 1,068 MWh, that is 1,130 kWh per capita.

Table 5
Simulation parameters.

	min	*max*	*step*
$P_{p\ FV}$ $[kW]$	125	1000	125
n_{core} $[adm]$	2	300	1
$Q_{H2\ LP\ lim}$ $[kg]$	1	10	1
P_{comp} $[kW]$	5	20	1
$Q_{H2\ CC}$ $[kg]$	5	40	1

Italian law on REC states that the maximum power for a single power plant is 1 MW [11]: in the simulation is assumed this limit for the PV plant. Maximum power for the electrolyser is assumed around the same PV peak power: 300 cores is the maximum value assumed for the Enapter electrolyser.

Regarding the parameters used in the simulation, their limit values and calculation step are indicated in Table 5.

For each power step of the PV plant, the combination of simulation parameters is investigated to obtain NPV positive, closest to zero and with maximum of hydrogen production in the reference year. In other words, for each of the eight cases defined by size of PV plant ($P_{p\ FV}$), a conditional optimization was carried out. The condition is that the NPV is positive, closest to zero; the optimization for each PV size allows to obtain the values for the parameters to maximise amount of renewable hydrogen produced. In fact, beyond the size of the photovoltaic system, the remaining four variables make it possible to size completely the PtG system, and then to obtain the optimal sizing of the whole plant. The variables define respectively the power of the electrolyser (P_{elect}) through the number of modules (n_{core}), the size of the low-pressure storage ($Q_{H2\ LP\ C}$) through the mass limit in LP storage ($Q_{H2\ LP\ lim}$), the compressor power (P_{comp}) and the size of hydrogen HP storage ($Q_{H2\ CC}$). It is important to note that NPV close to zero is the limit condition for economical sustainability. Starting from this limit conditions with a given PV size, decreasing the size of the PtG system by diminishing number of electrolyser modules and consequent storages, NPV becomes greater than zero, obtaining full economic feasibility. So, the existence of these limit conditions for each PV size, allows to orientate in the choice of the economically sustainable dimensioning of the system. Results of optimization are shown in Table 6 for each PV case, where main numerical results have been indicated: net present value of the cases (*NPV*), levelized cost of hydrogen (*LCOH*) and total amount of hydrogen delivered and sell in the market annually ($Q_{Del\ ann}$) have shown in Table 6 other than main recalled parameters.

Negative value of LCOH indicates that subsidies for shared energy have a higher impact on cash flow in comparison with capital cost and O&M cost.

Distribution of renewable energy in different cases is detailed in Fig. 6.

Case #1 has not enough renewables to produce hydrogen: the PV plant produces energy that is fully shared with REC and consumed by it. Without hydrogen supply chain, NPV is largely positive. Cases from #2 to #5 allow to produce hydrogen from renewables, selling it at the same price of fossil hydrogen (5 €/kg @200 bar), maintaining a NPV positive around zero. Case #2 have a much more than zero NPV because increasing electrolyser size to have NPV equal to zero, no extra hydrogen would be produced in the year: as shown in Fig. 6 there is no relevant energy out of the area to convert in more hydrogen by more electrolyser core. In this condition have no sense obtain a NPV equal to zero buying a greater electrolyser that have no energy to produce hydrogen. For this reason, case # 2 has not NPV around zero.

An amount between hundreds or thousands of kilograms of hydrogen per year can be produced and sold at the same price and pressure value of fossil hydrogen from large SMR in cases from #2 to #5. Smaller electrolyser respectively for each cases (from #2 to #5) and consequently smaller storage systems, allows to sell hydrogen at the same price of hydrogen from SMR with a NPV greater than indicated in Table 6. In other words, there is the possibility to start a production of renewable hydrogen that makes the investment sustainable from an economic point of view (NPV greater than zero) by under sizing the PtG chain in comparison with that producing the maximum amount of hydrogen with a certain PV plant as indicated in Table 6.

In case from #2 to #5, enough shared energy allows to obtain economic subsidies that sustain the PtG supply chain more than the sale of hydrogen and electricity out of area (not shared in REC): in case #2 this situation is so impactful that LCOH is negative.

Table 6
Results of simulation.

Case number	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*
$P_{p\ FV}$ [kW]	*125*	*250*	*375*	*500*	*625*	*750*	*875*	*1000*
n_{core} [adm]	-	*31*	*56*	*46*	*18*	-	-	-
$Q_{H2\ LP\ lim}$ [kg]	-	*1*	*1*	*1*	*1*	-	-	-
P_{comp} [kW]	-	*5*	*5*	*5*	*5*	-	-	-
$Q_{H2\ CC}$ [kg]	-	*13*	*32*	*36*	*18*	-	-	-
$Q_{H2\ LP\ C}$ [kg]	-	*2*	*5*	*4*	*2*	-	-	-
P_{elect} [kW]	-	*95*	*171*	*140*	*55*	-	-	-
NPV **[k€]**	*144.6*	*84.0*	*1.2*	*0.2*	*1.2*	*8.7*	*-72.6*	*-158.2*
LCOH [€/**kg**]	-	*-8.33*	*4.96*	*4.99*	*4.94*	-	-	-
$Q_{Del\ ann}$ [kg]	-	*494*	*2,112*	*3,168*	*1,692*	-	-	-

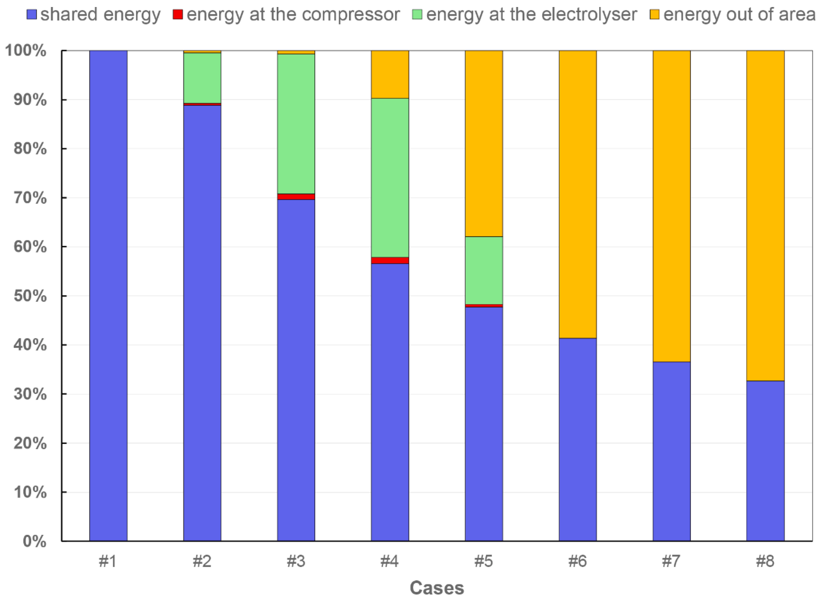

Fig. 6. Renewable PV energy distribution in different cases.

Increasing PV size, the shared energy perceptually decreases as indicated in Fig. 6, and consequently the economic subsidies. In the case #6 with a PV plant of 750 kWp system is just economically sustainable without hydrogen production (NPV equal to 8.7 k€): in case #6 PV size does not allow to increase significantly shared energy and the marginal energy produced in comparison with case #5 flows out of area away from REC.

Assumed price of energy is not enough for feasibility of the last three cases (from #6 to #8), and percentage of shared energy is too low. In them no production of hydrogen is allowed: in case #6 introducing the smallest PtG supply chain (only 1 core of electrolyser), NPV would be negative. In cases #7 and #8 NPV is negative without PtG supply chain. So, with electric price as assumed, a percentage of shared energy at least about 50% is necessary to obtain economic feasibility of a hydrogen PtG supply chain in a REC.

Case #4 and #5 are the best ones considering annual hydrogen sale

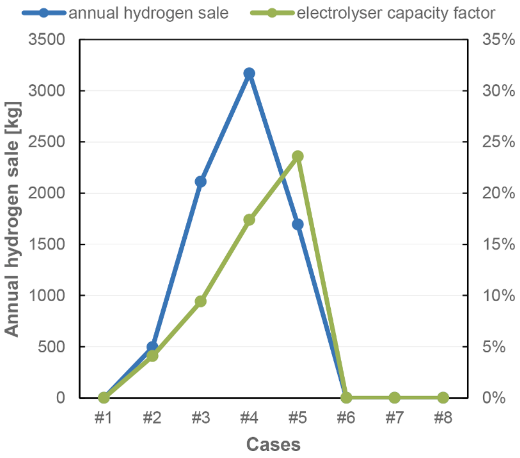

Fig. 7. Annual hydrogen sale and electrolyser capacity factor.

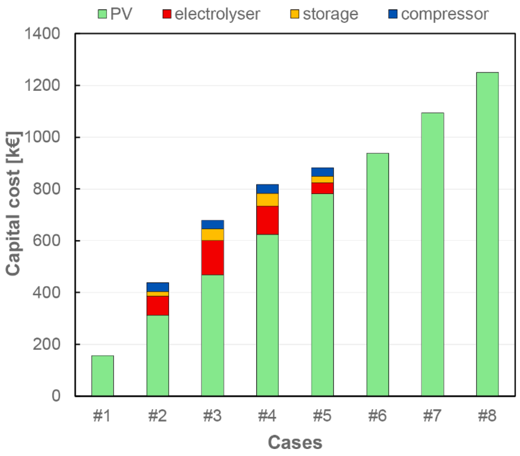

Fig. 8. Total capital cost overview.

(3,168 kg) and electrolyser capacity factor (24%) respectively. Capacity factor in case #5 is in line with Liponi et al. [47], but she stated a higher cost of hydrogen production.

These key performance indicators of presented analysis are shown in Fig. 7.

Three different conditions for PV size rise up from the study considering the same REC. A too small PV plant does not generate excess of renewable energy to convert into hydrogen: no PtG is achievable (case #1), even if, economically, the case is fully sustainable. A set of intermediate sizes of the PV plant generate both enough excess of electricity to be converted into hydrogen and a shared energy amount to obtain enough subsidies to economically sustain PtG chain (cases from #2 to #5). In this set optimal size can be define both to maximize amount of hydrogen annually produced and capacity factor of the electrolyser. A too big PV plant also if produces a lot of excess of renewable, generates perceptually too small amount of shared energy to sustain a PtG (case #6) or even the same PV additional power (case #7 and #8). In these last cases NPV is negative considering the only PV installation.

A general overview of total capital cost in different cases is indicated in Fig. 8 for different cases investigated. It can be noted that capital cost of hydrogen supply chain is not the most relevant in each case of the study in comparison with the capital cost of the PV plant that in any case is the predominant one.

4. Conclusions

This study explores production of hydrogen by electrolysis using excess of electricity in a Renewable Energy Community (REC) using a Power-to-Gas (PtG) scheme. Only residential electric users have been considered in the REC as case study, that are only consumers: no prosumers are assumed. Energy is generated by a single photovoltaic (PV) centralized plant. The study is defined for a small village in Central and the South of Italy, where thousands of villages are located with a good PV potential production. REC is composed by around 1 thousand people, grouped in 450 residential users. The proposed electrical layout describes a directly coupled electrolyser with the centralized PV plant. A storage system is defined, composed by low (35 bar) and high pressure (200 bar) cylinders, with a compressor that transfers hydrogen from first to second storage. No electricity is drawn by the grid by this electrolyser as well as by the compressor for storage purposes. The scheme presented is compliant with the European directives and the Italian legislation on REC. Italian incentive for shared energy in a REC is considered as well as revenue for selling electricity as well as hydrogen at the current lowest price in the Italian market (hydrogen from steam reforming fossil methane).

With assumed REC, eight different sizes for photovoltaic single plant in the power range allowed by Italian regulation have been explored (from 125 kWp to 1 MWp).

For each of them, in the study an optimal sizing of the PtG chain is presented at limit economic viable condition: power of both PV and electrolyser, capacities of the storages and power of the compressor has been defined to obtain a net present value (NPV) of the investment positive, closest to zero at the maximum of hydrogen production in a reference year. As general result, the study shows that there are different sustainable sizes of the PtG in as defined REC to allow a local green hydrogen market at the same selling condition of fossil hydrogen from a large steam reforming plant.

More in detail, the main findings can be summarised as follows:

- The sizing of PV plant in view of the REC dimension and consumption characteristic is a critical aspect for the economic feasibility of the hydrogen PtG in a REC. A PV plant undersized or oversized nullifies the benefit of the proposed PtG scheme in a REC.
- Shared energy amount in REC is a useful key factor to define an optimal sizing of the renewable power generation. In the range between around 50 and 90% of shared energy in comparison with total renewable energy produced in a REC, the economic subsidies allow to produce green hydrogen at the same selling price of hydrogen from large steam reforming fossil methane plant.
- The amount of hydrogen generated in the case of maximum production quota is around 3 tons per year with a 140 kW electrolyser and a 500 kWp PV plant.
- There are sizes of the PtG based on a REC that allow to generate hydrogen at minimum Italian price and obtaining a NPV greater than zero.
- An electrolyser directly coupled at a single PV centralized plant enslaved at a residential REC has a capacity factor (up to 24% in case of 55 kW electrolyser and a 625 kWp PV plant) in line with one enslaved at a PV plant fully dedicated at hydrogen production by a PtG system. In the case addressed in the study the minimum selling price of hydrogen is lower than in PV plant full dedicated to PtG.

In conclusion, a PtG scheme in a residential REC can produce and sell in Italy green hydrogen (@200 bar) at the same price of fossil hydrogen from large scale steam methane reformer. Italian subsidies at shared energy in a REC is the key factor for this result, that can enable developing of a green hydrogen local market.

In future works a sensitivity analysis on many parameters involved in the study could better define the impact of foreseeable variations of the components of the systems (particularly electrolyser, compressor, storage systems) and of the value of electricity: within next few years, such sectors could appear to be highly volatile. Moreover, it appears to be of interest in a future study to compare economic feasibility of a centralized PV plant with a decentralized one with the same overall power peak but integrated at user's level. Effect of distribution of renewable energy between self-consumed energy and shared energy on economic behaviour of a hydrogen PtG in a REC could be of interest.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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