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Integrating renewable energy communities and Italian UVAM project through renewable hydrogen chain

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ABSTRACT

Renewable energy communities (RECs) in Italy could play an important role in increasing the stock of electric renewable generation in the coming years. Their impact on the electric grid could be non-negligible. At the same time with increased electric generation from renewables, a greater need for electric national grid balancing is expected, preferably based on zero-emission energy storage. Based on currently existing entities in Italian regulation framework (i.e. REC and UVAM project), the present work proposes an original business model to create a storage of dispatchable renewable hydrogen to be used for balancing National electric grid. Hydrogen production is from excess of renewables in RECs constituted in the same area. UVAM project allows to access the ancillary services market with the minimum capacity of 1 MW that appears appropriate to the proposed scenario. Based on current technical-economic constraints of the technologies involved (electrolysis and both fuel cell and internal combustion engine fed by hydrogen), proposed business model is not day-present economic feasible: the return on investment is never positive. The cost forecasts available for 2035 indicate that the business model will be likely sustainable, with a net present value becoming positive for configurations with more than 3000 people involved in the RECs, with a photovoltaic penetration condition of 1.8 kWp/capita. This research work suggests an original business model for managers of RECs with an excess of renewables generation.

Introduction

Due to the increase in the diffusion of renewable energies in Italy, the state of the medium and low voltage (MV and LV) electric grid appears to be critical currently in many areas of the country. E-distibuzione (Enel group) is the biggest Italian electric distribution system operator (DSO) and it periodically publishes on line the state of the electric grid in a map with a qualitative graphical synthesis regarding the transport capability and quality of the service [1].

As declared on the web site, “through the map it is possible to obtain,

Abbreviations: ARERA, Italian Regulatory Authority of Energy, Networks and the Environment (in Italian language); ASM, Ancillary Service Market; BSP, Balancing Service Provider; CALA, Calabria region; CAPEX, Capital Expenditure; CNOR, Central-Northern Italy; CSUD, Central-Southern Italy; DAM, Day-Ahead Market; DSO, Distribution System Operator; ENTSO-E, European Network of Transmission System Operators for Electricity; FC, Fuel Cell; GME, Italian Energy Services Operator (in Italian language); HV, High Voltage; ICE, Internal Combustion Engine; IM, Intraday Market; JRC, Joint Research Centre of European Union; LCOE, Levelized Cost Of Energy; LHV, Lower Heating Value; LV, Low Voltage; MASE, Ministry of the Environment and Energy Security (in Italian language); MB, Balancing Market (in Italian language); MSD, Dispatching Services Market (in Italian language); MV, Medium Voltage; NORD, Northern Italy; NPV, Net Present Value; OPEX, Operational Expenditure; PEM, Proton Exchange Membrane; POD, Points of Delivery; PUN, Italian National Price (in Italian language); PtG, Power-to-Gas; PtP, Power-to-Power; PtX, Power-to-X; PV, Photovoltaic; REC, Renewable Energy Community; RED, Renewable Energy Directive; SARD, Sardinia; SICI, Sicily; SME, Small and Medium Enterprise; SUD, Southern Italy; TSO, Transmission System Operator; UVAM, Virtually Aggregated Mixed Units (in Italian language); C_a, capital cost in the year a; $C_{i,REC}(t)$, residential consumption in each REC (i); CM_a, , capacity market economical fee in the year a; $E_{i,Comp}(t)$, energy for hydrogen compression; $E_{i,Elect}(t)$, energy for electrolyser; $E_{i,PV}(t)$, energy produced by PV in each REC (i); $E_{se}(t)$, total shared energy; $E_{i,se}(t)$, shared energy in each REC (i); I_0, CAPEX incentives to REC in small municipality; *IF*, incentives tariff; $O\&M_a$, operation and maintenance cost in the year a; *OOF*, optimization objective function; $PP^{Max}_{auction}(t)$, maximum purchase price in ASM auctions; $Q_{H2\ CC}$, maximum mass of hydrogen in the HP common storage; $Q_{i,H2\ trans}(t)$, mass of hydrogen compressed at HP common storage; $Q_{Store\ HP}(t)$, mass of hydrogen in the HP common storage; $Q_{UVAM}(t)$, mass of hydrogen for electric generation in UVAM; $SP^{exp}_{UVAM}(t)$, expected electricity selling price; SP^{mean}_{UVAM}, mean annual electricity selling price.

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in an interactive and immediate manner, qualitative indications regarding the availability of network capacity, through a classification of territorial areas by level of criticality". The criticality is linked to the average residual electricity transport capacity and stability of the electricity grid, measured through the most relevant parameters (frequency and voltage on the grid during days). In general, the greater the connections of renewable energy on the electricity grid, the higher the criticality encountered. Considering the electric grid in the 104 Italian provinces monitored in E-distibuzione on-line tool [1], during the last period available (from March to May 2023) 89 provinces are in medium-high critical level (around 90 %), and the installation of additional renewable energy capacity will likely worsen this situation without investments empowering the grid or changing its topological structure. More in detail, the electric grid in the regions and provinces of Southern Italy appears to be in further difficulty due to the high renewable potential and the low electricity demand in those territories. Basilicata is the Italian region with the greatest difficulty in accepting new renewables, as both its two provinces present a medium-high criticality in the period considered. More in detail, carrying out an analysis at the high voltage (HV) level, it is estimated that counting the 71 HV/MV substations in the region, in 10 of them there is a usual inversion of the electrical flows from the DSO grid to the TSO (transmission system operator) one, with a transmission power level beyond the critical limit. In other 9 cases the substations are not always able to manage all the installed renewable power (the sections reach saturation of the transmission capacity). Globally in 27 % of HV/MV substations in Basilicata there are medium-high criticalities on the grid to manage the renewables installed in the area.

In Italy, as well as in the rest of Europe, the push to install further renewable capacity is still strong, to be compliance with the climate transition objectives for 2030: "the revised Renewable Energy Directive, adopted in 2023, raises the EU's binding renewable energy target for 2030 to a minimum of 42.5 %" (in 2022 the share of renewables in EU consumption was 22 %) [2].

The European Directive on Renewable Energy (RED II) [3] described Renewable Energy Communities (so called RECs) as a new tool to increase renewable energy stock for residential end-users, associations or small and medium enterprises (SMEs). In Italy the RED II Directive was adopted in November 2021 [4] and the full operative legislative framework was defined by Directorial Decree number 22 adopted on 23 February 2024 [5]. RECs can be developed within the territory served by a single primary substation (HV/MV substation). Many different RECs could be developed independently into the same primary substation: no limits have been defined on the number of RECs by regulatory framework. Therefore, based on different needs from citizens, associations or SMEs, many RECs probably will be established under the same primary substation, without any coordination among them.

As highlighted in our previous study [6], without using dedicated storage, shared energy in a REC is only a small amount of the renewable electricity produced, due to the decoupling between electric usual hourly consumption and renewable production (see Figure 10 in [6]). A great quantity of renewables produced in the REC will flow through the electric grid towards areas out from REC zone. Therefore, RECs that do not use electric storages will impact negatively on local electricity grid of DSO: more electricity than in the configuration without RECs will need to be managed by DSO electric grid flowing out from the HV/MV substation where the REC is installed. Therefore, electricity in excess produced by RECs could affect negatively on DSO grid, that often is currently already in crisis regarding transport capacity, as previously highlighted in Italian landscape.

Many studies in the literature consider the REC developing in Italy, as well as throughout Europe, and its potential effect on both DSO and TSO grids and on the stock of renewables. In our previously study [6] we shown that the amount of electricity flow out from the local market area of a residential REC based on both wind and solar without storage could be not negligible on the DSO grid. Introducing an electrolyser operating with a capacity factor around 30 %, this excess of electricity can definitely be reduced both in peak of power and in energy amount. Weckesser et al. [7] described the RECs impact on DSO grid and the relevance of an optimal sizing of photovoltaics and battery storage on it. Moreover, depending on the REC's operating strategy the LV grid loading can be reduced by up to 58 %. Mustika et al. [8] clearly expressed that RECs can have an important role in the stabilization of electricity TSO grid in particular with the provision of frequency reserve (manual frequency restoration of the tertiary reserve), anticipating some themes developed in the present work. The paper also described a case study in France based on battery storage and its positive effect on economics of the REC. García-Muñoz et al. [9] proposed a business model for a REC that offers reactive power as an ancillary service into the day-ahead and the intraday electric markets. Bartolini et al. [10] compared Power-to-Gas and battery storage in a REC with an high level of photovoltaic penetration and their effect on the local electric grid. Pastore et al. [11], considering an average electricity grid accommodation capacity up to 40 % of renewable electricity [12], investigated effect of Power-to-X in RECs to mitigate the impact on the electric grid. Sănduleac et al. [13] described a methodology that increases the accuracy of the monitoring tools for distribution power grids with a REC to decrease the impact on the electric grid. Herenčić et al. [14] reported a case for Croatian city of Križevci with a REC and its techno-economic effect on the energy sharing in MV and LV distribution grids. As D'Adamo et al. [15] stated, REC investments have an attractive profitability with a low level of risk: so could be a wide spreading model during the next years. This could generate a good effect on the stock of renewables in Italy, supporting a nation's energy independence and resilience by mitigating risks related to geopolitical issues and financial speculation.

High penetration of renewable generation in Italy also affects the national electric transmission system, potentially increasing instability of the HV grid. Terna is the Italian TSO and it has already started several projects during last decades to mitigate the effects of renewable energy on its own HV transmission system. The Italian UVAM (in Italian language Unità Virtuali Abilitate Miste, i.e., virtually aggregated mixed unit) project is a key initiative by Terna to integrate intermittent renewable energy assuring stability in the grid from distributed energy resources [16].

Started in November 2018, the UVAM project was reviewed in different papers. Schwidtal et al. [17] underlined the main aspects of the UVAM project and reviewed it after 2 years of execution. Due to the inherently unprogrammable nature of most renewable energy sources, electricity markets face an increasing volatility and need for balancing from ancillary service markets (ASM) to stabilize the TSO grid. ASM was dominated until now from fossil fuel-based power plant, but this condition must decrease during next years due to face out from fossil energy. Aggregation of multiple small units to one large unit through a so-called virtual power plant [18] is a solution to create more distributed resources for ancillary services on the grid, possibly using directly renewable energy and renewable energy storage (i.e. hydrogen). Through the aggregated dimension, they can potentially participate on electric market and more in detail at ASMs that each individual unit by itself would not be able to access (there's a minimum power dimension). Aggregation defining virtual bigger power plants is an essential building block for an effective energy transition and an increasing integration of renewables [19].

Also Gulotta et al. [20] in 2020 stated constitution of a relevant number of aggregators (entities that constituted UVAMs and that participated to ASM) that allowed to led to a more competitive auction market in Italy. in December 2021, Terna itself [16] stated that more than 220 UVAMs were qualified with a power of approximately 1280 MW and with 1072 PODs (Points of Delivery) involved. UVAMs were managed by 17 different Balancing Service Providers (BSPs). According to ENTSO-E [21], a BSP is an agent that can offer balancing services to the TSO.

Residential users too, if aggregated, can provide services on ASM,

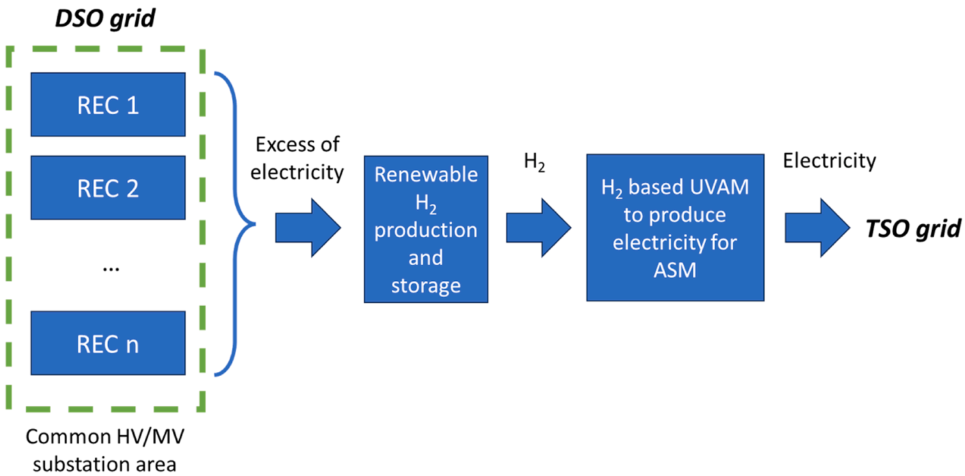

Fig. 1. Simplified scheme of the proposed system.

and consequently also a REC, through storages and electric measuring technology, is able to provide flexibility services to the grid [22].

Cancro et al. [23] described a similar scenario and proposed a new methodology to determine the optimal revenue of a UVAM based on residential users. They proposed as future work to consider REC as aggregator, but not developed it. Forouli et al. [24] reviewed the deployment of demand side flexibility in different European nations, to identify best practices and main barriers. In a comparative way they reviewed system developed in United Kingdom, Belgium, Italy and Greece. They underlined that RECs can be considered as enabling entities for participation to all electric markets (ASM in particular).

An UVAM based on renewable energy needs a storage that allows renewable energy to be dispatched in the electric market. Hydrogen can surely serve this purpose even if the round trip efficiency currently appears limited and lower than battery systems [6,25,26]. The low round trip efficiency implies that frequently the costs associated with a Power-to-Power (PtP) based on hydrogen is not sustainable from an economic point of view [6].

The aim of this work is to propose and investigate an original techno-business model that allows to produce renewable hydrogen from excess of renewables at a low cost by exploiting REC's incentives and using it to produce dispatchable renewable electricity for the richest electricity market existing in Italy (ASM) through UVAM project (Fig. 1).

The production of hydrogen within a REC allows both to avoid the problem on the electricity DSO grids due to high level of renewables penetration, and to produce renewable hydrogen at a low cost due to incentives. The UVAM project allows in Italy to minimize the size of the power plant (only 1 MW as better described in the following Section) to access ASM, based on currently regulatory framework. To the best knowledge of the authors, no paper describes a such system that exploits an inherent problem of stability on DSO grid potentially created by RECs' deployment in a territory to solve a stability problem on TSO grid through UVAM fed by renewable excess from RECs. This represents the novelty of this work: in the current regulatory and legislative Italian context, we propose both a solution to the problems described above of management of the excess of renewable energy produced by RECs in a local grid and renewable balancing electricity TSO grid by ASM using UVAM based on renewable hydrogen. Taking into account REC's and UVAM's legal framework, this study offers a scenario that fully complies with the rules and regulations currently in effect in Italy, as well as considering technical economic state of the art.

Ferrucci et al. [27] concluded in their recent study that from a regulatory point of view, as RECs are already acknowledged by specific supporting schemes, they could not be acknowledged as UVAM too, to operate on the market offering ancillary services on the electric market. Our study proposes a techno-business model to overcome such an objection by proposing an original balance of plant of the equipment that allows RECs to participate in the ASM.

Brusco et al. [28] claimed a potential role of RECs in providing additional ancillary services on electric market, also using hydrogen as a storage system. They described a storage system in RECs (daily based on batteries and seasonal based on hydrogen) to increase autarchy of the RECs (self-consuming of electricity from local renewables) and to participate to ASM considering only 25 % of energy stored is considered to be dedicated to the provision of ancillary services. Furthermore, Brusco's paper does not take into account the minimum limit of 1 MW for defining an UVAM in Italian regulatory framework (see following Section), appearing to be rather just a suggestion. In fact, all cases studies in Brusco et al. [28] considered 20 kW as maximum power adsorbed from or injected in the electric grid to assure ancillary services, which is a quantity incompatible with the UVAM project. Moreover, no detail on efficiency or cost of hydrogen supply chain were declared, so a comprehensive economic analysis was not fully accomplished. In the opinion of the authors, a different sizing of the systems, an alternative use of renewables and a diverse business model can develop a feasible strategy to provide auxiliary services on the electric market, based on RECs.

Crespi et al. [29] described a technical scenario very similar to what is the purpose of this work, in fact the technological architecture presented corresponds to what is analysed in the present study, as well as the business model for participation in the electricity market. However, the fundamental regulatory element enabling the business model (i.e. regulatory Italian framework defining RECs) is lacking.

Material

Italian electric markets and UVAM project

Crespi et al. [29] showed an accurately description of the Italian electricity market and its functioning, partially taken up again below. In Italy there are various electricity submarkets to respond to different functions of the electricity distribution service. The Day-Ahead Market (DAM) is an auction market to provide base load generation, where participants (both producers and consumers) trade hourly electricity quantities for the next day by submitting bids indicating the quantity and the minimum and maximum sell/purchase prices. After each market session, the intersection of demand and supply prices defines the actual price (marginal clearing price) for each time slot and all the generation (consumption) units that bid a lower (higher) price are scheduled to generate (consume). The solution of the market balance takes into account also the transmission capacity limits between different zones of the electric grid (bidding zones), which are defined by Terna, generating

Table 1
Electricity sale price on ASM (MSD ex-ante) in 2023 in Italian bidding zones.

	CALA	CNOR	CSUD	NORD	SARD	SICI	SUD
mean value (all year sessions) [€/MWh]	188	185	207	201	173	212	207
ASM's active hours in 2023 [hours]	722	1665	1869	5090	895	1545	937
maximum price [€/MWh]	305	320	331	351	265	303	335
minimum price [€/MWh]	120	130	122	120	145	122	123

different prices (zonal prices) if they are saturated. Zonal prices are applied for the remuneration of the generating units, whereas the accepted demand bids are conversely remunerated at the national single price (in Italian language Prezzo Unico Nazionale i.e. PUN), equal to the average of the zonal prices weighted on the quantities. In this study zonal prices and PUN of 2023 were used, inferred from GME (in Italian language Gestore dei Mercati Energetici, i.e., Energy Services Operator) website [30].

The Italian electricity market provides also the Intraday Market (IM) and the already mentioned ASM. As the DAM, the IM is an auction market where hourly energy blocks are traded to modify the preliminary schedules defined at DAM closure. Conversely, the ASM is the market where Terna procures resources for the management and control of the system, such as frequency regulation, control of congestions, voltage regulation, etc. The Italian ASM consists of a scheduling stage (in Italian named Mercato dei Servizi di Dispacciamento – MSD ex-ante) and the Balancing Market (Mercato del Bilanciamento - MB), each of them composed of multiple sessions. On the MSD ex-ante, Terna accepts purchase and sale offers to solve residual congestions on the network and establish adequate reserve margins. On the MB, which is open throughout the same day of operation, Terna accepts purchase and sale offers to perform the secondary regulation service and to maintain the balance between electricity injection and withdrawal in real time. In both MSD ex-ante and the MB, bids are remunerated with a pay-as-bid mechanism, i.e., at the offered price. They are normally most profitable electricity markets where the price of electricity can even be a time-and-a-half DAM hourly price [30,31].

Electric provider who wants to participate in electricity markets must be qualified according to the network code established by Terna [32].

The UVAM project represents the first integration in Italy of distributed energy resources to supply ancillary services to the power DSO grid such as balancing, tertiary reserve and congestion management in MSD ex-ante market [20].

With the aim of increasing the number of entities that could participate in the ASM beyond large electricity production power plants (equal or greater than 10 MVA), new rules were established in 2017 defining for the first time the UVAM as new aggregated entities [33]. New entities not obliged and too small to participate in the ASM were admitted to it, constituting a virtual bigger power plant through aggregation. As stated by Gulotta et al. [34] the admitted entities were small power plants, stationary energy storage systems or also electric vehicles.

As recalled by Gulotta et al. [20] in the early stage of UVAM project the minimum bid size to access the market qualification process was initially set at 10 and 5 MW, respectively for loads and generation plants. In 2020 [35] the minimum size threshold has been reduced to 1 MW for all type of UVAM [36].

The UVAM project has adopted a remuneration scheme based on both the energy dispatched in the ASM daily sessions (i.e. remunerated as pay-as-bid in €/MWh) and long-term capacity contracts, linked to the expected availability of the plant acting in regulation (i.e. remunerated for capacity as €/MW per year based on annual auction in capacity market) [20].

In this study the ASM sessions of 2023 were considered in all the seven Italian bidding zones: Table 1 summarizes the ASM in Italy in 2023 inferred from [31]. The considered market areas are CALA (Calabria region), CNOR (Central-Northern Italy), CSUD (Central--Southern Italy), NORD (Northern Italy), SARD (Sardinia), SICI (Sicily), SUD (Southern Italy) as described in Italian MSD [37].

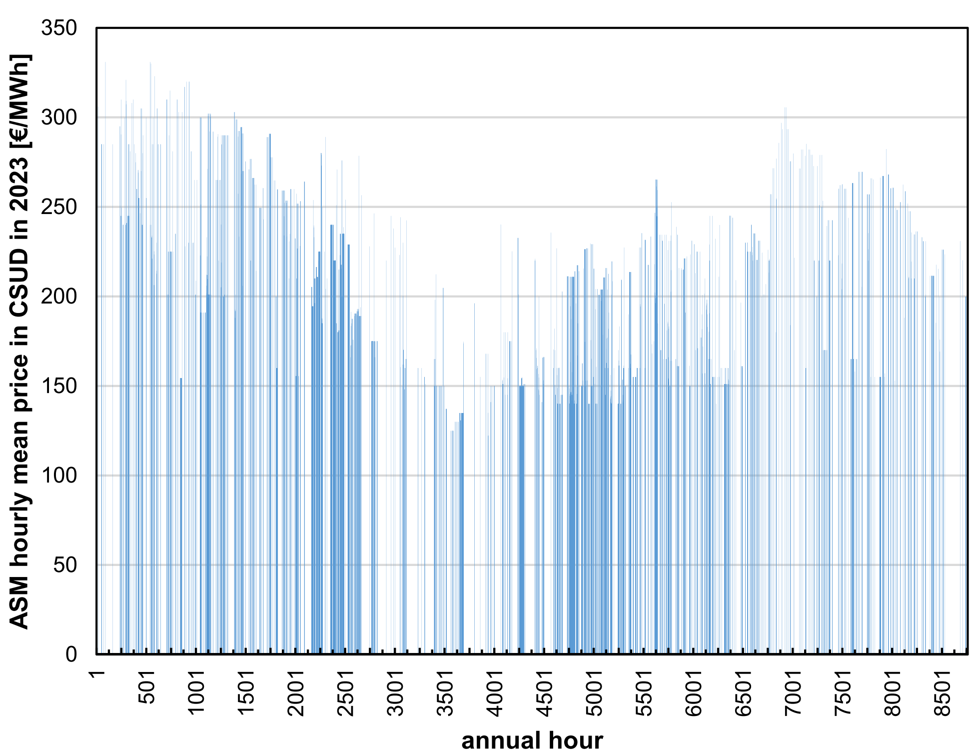

Fig. 2. Mean price in ancillary service market in CSUD bidding zone in 2023.

The market area with the greatest quantity of electricity exchanged (NORD) has a greater number of active market sessions (number of active hours) to prevent network imbalances. Bidding zones with lower electricity demand and greater predictability (CALA, SARD) showed ASM's active hours only around 10 % of annual hours. An example of evolution of mean price in ASM during each hour of the year in CSUD bidding zone is indicated in Fig. 2, such as an indication of the active market sessions of the ASM.

Based on available hydrogen between the seven different market areas in Italy (bidding zones), it is possible from any area to dispatch electricity to other areas, following successful auctions.

Renewable energy community in Italy

A Renewable Energy Community is a legal entity as stated in article 2 paragraph (16) of RED II [3]. 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".

Members of a REC are producers, consumers or prosumers (both producers and consumers) of renewable energy. In article 8 of the reference Italian law [4], "shared energy" is legally defined, as the energy produced by renewables and consumed in the same hour by users within a REC through the DSO grid. Furthermore in detail as defined in article 2, paragraph 1), letter q) of Dlgs 199/2021 [4], 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. In February 2024 operative rules to constitution and managing for a REC in Italy was published in a specific decree [5] by the MASE (Ministry of the Environment and Energy Security), defining techno-economic rules for electric market area and subsidies representing the incentive mechanism. The geographical area to define a REC was established as the HV/MV substation feeding area in the DSO grid (primary substation).

As recently summarized by D'Adamo et al. [15], recipients of the measures include not only RECs, but also the so-called collective self-consumption of energy from renewable sources (composed by groups of consumers operating within the same building or residential complex); and individual self-consumption of energy from remote renewable sources, in which a sole entity (company or private residential user) exchanges in the some hour energy from various production and consumption sites under its ownership and management. The incentive is assigned for 20 years and varies according to the size of the renewable source plants generating the shared energy and the zonal price:

- power plants with size less than or equal to 200 kW: tariff = 80 + max (0; 180 - zonal price) €/MWh with a maximum of 120 €/MWh;
- power plants with size greater than 200 kW and less than or equal to 600 kW: tariff = 70 + max (0; 180 - zonal price) €/MWh with a maximum of 110 €/MWh;
- power plants with size greater than 600 kW and less than or equal to 1 MW: tariff = 60 + max (0; 180 - zonal price) €/MWh with a maximum of 100 €/MWh.

In addition, for photovoltaic systems, there is an addition of 4 €/MWh or 10 €/MWh if located in central or northern Italian regions respectively, due to lower insolation in comparison with southern ones. Renewable plants installed in REC until 2026 in municipalities under 5000 inhabitants receive a 40 % non-refundable loan for installations: in these cases, the incentive on shared energy is reduced by 50 %. The new Italian regulation [5] also requires that a SME participating in the REC cannot have incentives corresponding to more than 55 % of the shared energy. The excess quota over 55 % must necessarily benefit directly citizens, to realize social and environmental improvements of the area where REC is established.

Table 2
Single core characteristics of the electrolyser.

power consumption with auxiliary [kW]	3.05
power consumption to produce hydrogen [kW]	2.4
mass flow rate [g/hour]	64
efficiency [% LHV]	70 %

Power generation by photovoltaic plants in the RECs

In a REC, photovoltaic panels can be mounted in various ways, depending on their integration on roofs of pre-existent buildings or installation on the ground with or without solar tracking systems. The annual productivity and the daily production curve will depend on the carried-out installation and will have an impact on the definition of shared energy in view of REC incentives.

Using data from JRC PVGIS initiative [38] a single kW peak PV system can be characterized considering different mounting options, location of the plant, historical irradiation data. Hourly annual production of energy PV can be inferred and this time resolution is useful to define the shared energy based on hourly annual consumption of REC members.

A highly penetration PV condition in the area where the REC is based is a fundamental premise for this study, that is considering only PV as energy renewable source. In Italy REC can be realized with members and renewable plants connected to the same primary substation. The highest PV installed power per capita in Italy in 2023 is 0.9 kWp/capita with the mean Italian value of 0.5 kWp/capita [39]. Current PV Italian total amount is 30 GWp and in 2030 would be around 80 GWp [39]. A x2.6 increase is expected in very few years that will impact also the PV per capita, with a highest value at 2.3 kWp/capita and a mean value of 1.3 kWp/capita.

Hydrogen production, storage and use

Modular type electrolyser enables a better matching with renewables, due to partialization of the switching on of the individual modules. It is supposed a PEM technology that assures an efficiency of 70 % based on lower heating value (LHV) of the hydrogen [40]. The electrolyser architecture is assumed similar to a modular Enapter EL 2.1 type [41]. The inferred data of a single core electrolyser are summarized in Table 2.

Pressure storage of the hydrogen is a common solution. A double pressure level (35 and 200 bar) is indicated in our previous study [42].

In a PtP approach internal combustion engine (ICE) and fuel cell (FC) are considered usual solutions in literature [43] to produce electricity using stored hydrogen produced by renewables. Due to different technological maturity, there are differences in particular regarding the efficiency and, above all, the cost of them. In fact, while for a hydrogen ICE the capital cost currently stands at around 800 €/kW [43], for fuel cell technology it stands at between 1600 and 2000 €/kW [43] with a peak at 3000 €/kW in Crespi et al. [40]. The efficiency values are also different: based on LHV the usual efficiency for an hydrogen ICE is 45 % [43] while hydrogen fuel cell allows efficiency between 50 % and 60 % [40, 43].

Considering that the electric generation in ASM is not continuous (typical active session also of only one hour) but which could involve multiple switching on and off even during the same day, it is important to consider warm up both consumption and time for the power generation system. Crespi et al. [44] characterized a 1 MW fuel cell system warm up stage: a hydrogen consumption of 20.9 kg in warm up was inferred with a net electric production of 250 kWh and a warm up time

Table 3
Economic parameters.

Parameter	Value	Ref.
Lifetime, N [year]	20	[48]
Interest rate, d	5 %	[48]
Electrolyser capital cost [€/kW]	1185	[40]
Storage (200 bar) capital cost [€/kWh]	13.5	[49]
Compressor capital cost [€/kW]	1600	[40]
Hydrogen ICE capital cost [€/kW]	794	[43]
Hydrogen Fuel cell capital cost [€/kW]	3292	[40]
Electrolyser O&M cost [€/kW/year]	19	[48]
Storage O&M cost [of CAPEX/year]	0.5 %	[50]
Compressor O&M cost [of CAPEX/year]	1 %	[40]
Hydrogen ICE O&M cost [of CAPEX/year]	5 %	[43]
Hydrogen FC O&M cost [of CAPEX/year]	2 %	[40]
ARERA shared energy fee [€/kWh]	0.009	[51]

of 46 min.

Economic facts

A Levelized Cost Of Energy (LCOE) [45] and Net Present Value (NPV) can be used for the evaluation of different cases.

$$\begin{cases} LCOE = \dfrac{\sum_{a=0}^{N} \dfrac{C_a + O\&M_a - (CM_a + I_0)}{(1+d)^a}}{\sum_{t=0}^{N} \dfrac{E_a}{(1+d)^a}} \\ NPV = \sum_{a=0}^{N} \dfrac{C_a + O\&M_a - (CM_a + I_0)}{(1+d)^a} \end{cases} \quad (1)$$

Beyond the usual annual (a) expenditure items due to capital cost (C_a) and operation and maintenance cost ($O\&M_a$), two items are considered in decreasing the LCOE: the economical fee assigned in the capacity market by auctions for generation plants serving the ASM by UVAM (CM_a) and CAPEX incentive to REC constituted in Italy in municipalities with less than 5000 inhabitants (I_0). The 2023 capacity market auction is considered with an outcome for the new plants in Sicily of 75,000 €/MW per year [46]. Based on appendix 2 of Ministerial Decree number 414 adopted on 7 December 2023 [47], energy storage system in a REC constituted in municipality of less than 5000 inhabitants can receive a non-repayable loan of 40 % of the capital cost.

In the Eq. (1), d is the interest rate considered in the lifetime N for the investment. At the denominator, E_a represents the electricity sold in ASM in the considered year by UVAM.

In the operational cost the main relevant one is the electricity cost for the electrolysis to produce hydrogen: considering current commercial offers available for SMEs by electricity Italian suppliers, purchase price was defined as hourly PUN price in 2023 [30] with a surcharge commercial fee equal to 37 €/MWh. The mean purchase price in the typical year (assumed 2023) is 164 €/MWh.

To define the incentives for shared energy in the REC, the hourly zonal price in 2023 in Sicily is considered [30]: mean zonal price in the typical year (assumed 2023) is 125 €/MWh.

Economic values considered in the simulation are shown in Table 3.

Shared energy fee by ARERA (Italian Regulatory Authority of Energy, Networks and the Environment) is the incentive which is assigned due to the reduction of electricity losses on the grid due to the creation of a REC, in addition to whom based on Italian government incentives [5].

Case study

This study integrates different technologies to create the intended system (Fig. 3).

In a sole HV/MV substation area (indicated with a rectangle in green dotted line) where many RECs have been constituted (indicated with rectangles in black dotted line), a H_2 company (indicated with a rectangle in yellow dotted line) produces, stores and sells hydrogen from excess of renewables form each REC. The H_2 company is member of each REC, by connecting an electrolyser per each REC to DSO grid in the same HV/MV substation area. So, each REC is composed also by an electrolyser that drains excess of its renewables to produce hourly hydrogen, obtaining incentives for shared energy, otherwise flowing out of local DSO grid.

The H_2 Company is a SME and owns different electrolysers, each dedicated at a different REC using a different POD. The hydrogen produced by the H_2 Company from all the RECs in the HV/MV substation area is compressed and stored in a common storage system, transforming renewable energy into dispatchable energy ready for balancing the electricity grid.

The H_2 Company sells hydrogen to an electric company that manage a UVAM based on a 1 MW generating system (FC or ICE). The H_2 company cannot coincide with the electric company that manages the

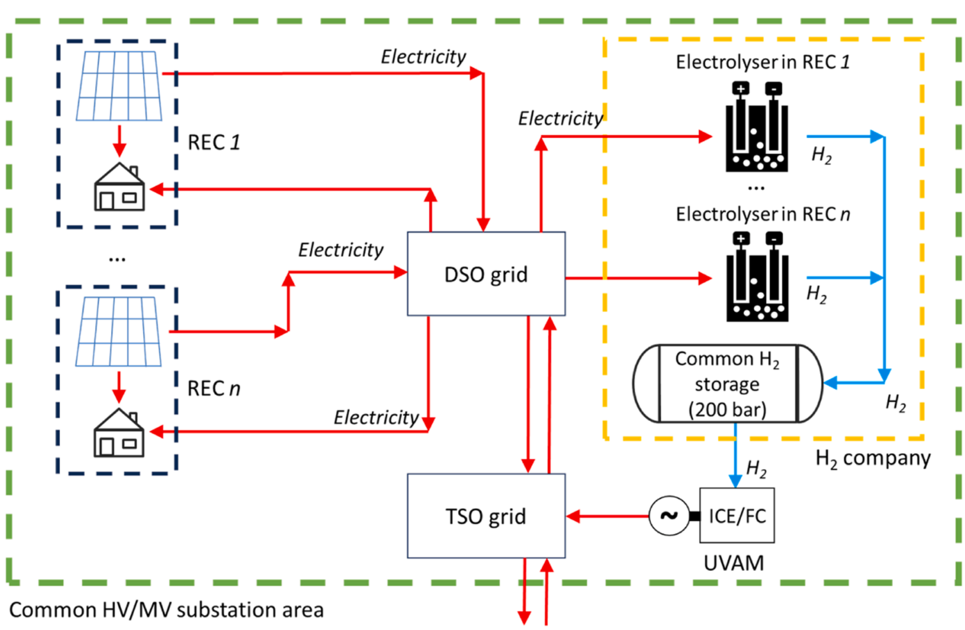

Fig. 3. Scheme of the proposed system with the essential entities and flows.

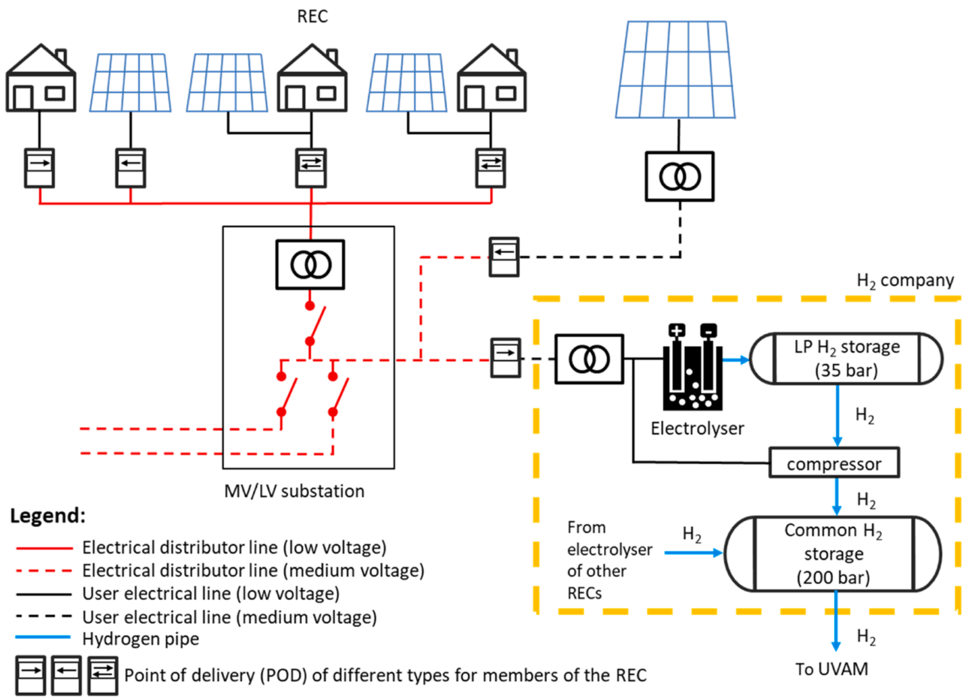

Fig. 4. Electric layout of a typical REC integrating a member with hydrogen production chain.

UVAM because under current Italian regulation [5] an electricity production and distribution company cannot be a member of a REC.

Based on available hydrogen in the storage of H_2 company, UVAM offers electricity auction shares in only upward-mode in daily ASM in all seven Italian different electric zones: it is supposed that there is enough interconnection capacity between the Italian zones to assure the transmission of electricity from one area to another. Electric connection of UVAM is directly at TSO grid inside the electric area where is based the RECs.

The proposed scheme is compliant with current Italian regulatory framework.

More in detail, each REC defined in this study has a layout as described in the Fig. 4.

REC is supposed to be composed by residential members, stand-alone PV plants (integrated or not with the buildings) and H_2 company through one electrolyser dedicated the specific REC. The residential REC members are both passive members (electric consumers), or prosumers (both producer and consumer). Power generation is only by PV, that are connected both at LV or MV level.

PV can be both integrated in the grid of residential buildings (partially self-consumer) or not. No battery storage is considered at prosumer level. Consequently, each POD defining the member of the REC can be monodirectional in purchasing or in selling of electricity (only one arrow in the icon to the right or to the left respectively) or bidirectional (two arrows in the icon) for the prosumers as described in Fig. 4.

Methods

The approach adopted in this study is discussed in this section.

Energy and hydrogen flows: mathematical model

In this study, the worst case for PV electricity production in the RECs is considered: all the PV panels is supposed integrated into the roof of the buildings without both solar tracking system and optimal slope (the same slope of the common roof in Italy is assumed). Therefore, a slope of 17 degrees with South orientation is considered. Supposed location for the plant and analysis is the area of Caltanissetta in Sicily (in decimal degrees latitude 37.498 and longitude 14.070) where is supposed RECs' location and hydrogen production and use chain by UVAM. The typical solar year is 2020 that is the last one available on JRC PVGIS on line tool [38]. The annual PV specific production is 1474 kWh/kWp considering constrains above defined.

The electrical consumption of the residential members of the REC is that presented in our previous study [42] and therefore can be directly correlated to the number of inhabitants taking part of the RECs.

Mathematical model for the characterization of consumption of REC, PV production, hydrogen production and storage is borrowed from our previous paper [42], so it is not here described. For common quantities the same nomenclature has been used here. To consider a set of RECs each one with a hydrogen producer member, mathematical model is reviewed in comparison to [42]. In each hour in the year (t) and for each REC (i) of the n composing the system, energy produced by PV ($E_{i,PV}(t)$) is drawn first for residential consumptions ($C_{i,REC}(t)$), than for hydrogen compression ($E_{i,Comp}(t)$) to move a quantity of hydrogen from low pressure storage to high pressure common storage $\left(Q_{i,H2\ trans}(t)\right)$, than to produce hydrogen ($E_{i,Elect}(t)$) by the electrolyser belonging to each REC. Hydrogen production happens if the mass of hydrogen in the high-pressure hydrogen common storage $\left(Q_{Store\ HP}(t)\right)$ is less than its limit ($Q_{Store\ HP}(t) < Q_{H2\ CC}$), and when there is an excess of renewables not used for residential uses or to compress hydrogen. No energy produced out of each REC is used to compress or produce hydrogen. So, electrolyser and compressor follow the PV excess after residential consumption. The shared energy in each REC ($E_{i,se}(t)$) in this configuration is describe in each hour of the year (t) and for each REC (i) by the following equation

$$E_{i,se}(t) = \min\left(C_{i,REC}(t) + E_{i,Comp}(t) + E_{i,Elect}(t);\ E_{PV}(t)\right) \tag{2}$$

Finally, if there is still availability of renewable electricity over power consumption from residential use, production and storage of hydrogen, this is fed into the grid and will be absorbed outside the area of influence of the RECs.

Total shared energy in the system is defined by

$$E_{se}(t) = \sum_{i=1}^{n} E_{i,se}(t) \quad (3)$$

where n is the number of RECs in the area involved in the system. Eqs. (2) and 3 are compliant with RED II and Italian reference law to define shared energy to estimate the incentives to electric flow in the RECs.

Each hour in the year, the electric company that manages UVAM evaluates the maximum purchase price in ASM auctions in all the seven Italian market zones ($PP^{Max}_{auction}(t)$). If this price is higher than expected selling price from UVAM ($SP^{exp}_{UVAM}(t)$), electric company activates the electricity generation at the considered time (t) if the hydrogen storage in the previous hour (t-1) is enough both for electric generation and eventually warm up. In fact, the state of the power plant at the (t-1) hour has to be evaluated: if the plant was running, it is sufficient that in the storage there is hydrogen for another hour of production, otherwise an extra quantity of hydrogen has to be considered for the warm up.

Hour by hour, the storage of hydrogen will be increased by the quantity produced by the electrolysers and decreased by the quantity absorbed for the operation of the UVAM

$$Q_{Store\ HP}(t) = Q_{Store\ HP}(t-1) + \sum_{i=1}^{n} E_{i,Elet}(t)\cdot\eta_{Elect} \Big/ LHV_{H_2} - Q_{UVAM}(t) \quad (4)$$

where $Q_{UVAM}(t)$ is the hydrogen for electric generation in UVAM with or without warm up, η_{Elect} is efficiency for FC or ICE (50 % or 45 % respectively) and LHV_{H_2} is lower heating value of hydrogen (Table 2).

The economic values of the energy input or output to the system are valued with the prices indicated previously. Out of caution and given the little weight it has in the simulations developed below, the electricity produced in warm-up was not economically valorised, while the quantity of hydrogen consumed is taken into consideration.

Constrains and optimization for sizing

The peak power of all the PV plants is supposed to be less than 200 kWp and all the REC is supposed to be constituted in municipalities with less than 5000 inhabitants: based on current Italian regulation [47] these considerations define the 40 % non-refundable loan for the CAPEX of hydrogen storage system and the incentives tariff (IT) as in the following equation:

$$IT = 0.5\cdot min\begin{cases} [80 + \max(0; 180 - zonal\ price)]€/MWh \\ 120\ €/MWh \end{cases} \quad (5)$$

where 0.5 factor is the effect of non-refundable loan.

The whole system is supposed to be realized in internal area of Sicily, in Caltanissetta area: an annual production of 1474 kWh/kWp is inferred as described in previous section.

PV per capita is set at 1.8 kWp/capita, in line with Italian evolution described in previous section for a highly penetration PV condition in the area where the REC is based. The 2023 capacity market auction for the new plants in Sicily of 75,000 €/MW per year [46] is considered as mentioned above, such as economical facts of Table 3.

In the simulation carried out for the twenty years of operation of the proposed system, the values of both electric zonal price and PUN are not modified based on future trends. The same consideration for the ASM, that is considered equal to 2023 each year of the simulation.

Several cases have been simulated by varying the total number of inhabitants involved in all the RECs: it is not relevant to discriminate whether those inhabitants are collected in one or more RECs and therefore whether there are one or more electrolysers within the H_2 company. Eight different simulations were carried out starting from 2500 inhabitants up to 20,000 inhabitants involved in the RECs. The number of inhabitants uniquely defines the installed photovoltaic power. In all cases, the UVAM is based on 1 MW power plant, analyzing both fuel cell and internal combustion engine solution to evaluate the

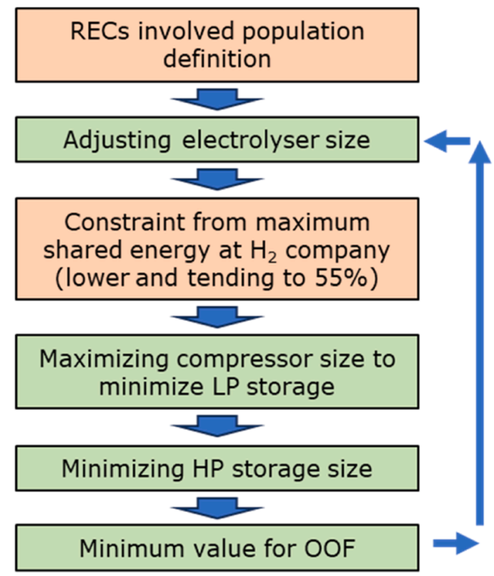

Fig. 5. Flowchart for sizing and optimize the system.

impact of different efficiency and different CAPEX and OPEX. This size is the minimum one allowed by Italian electric market, minimizing the size of the inhabitant involved and allowing the probability to realize the presented study.

The sizes of the other systems (electrolyser, low pressure storage, compressor, high pressure storage) was established with an optimization process. Optimization objective function (OOF) is the difference between LCOE and annual mean selling price for electricity produced by UVAM assigned in hourly auctions over the year in the seven market areas of Italy (SP^{mean}_{UVAM})

$$OOF = LCOE - SP^{mean}_{UVAM} \quad (6)$$

Positive values of the optimization function indicate a not economically sustainable investment. The more negative the values, the more profitable the investment is. Optimization criteria is based on techno-economic requirement indicated in the flow chart in Fig. 5, for each size of inhabitants considered in the RECs.

Results

Considering both an UVAM based on a fuel cell and on an internal combustion engine, the results of the optimizations are shown in the Fig. 6 considering the OOF as RECs size changes (number of people in all the RECs in the system).

In both cases the proposed system does not reach the minimum values for economic sustainability as the objective function is always positive. By increasing the size of the population involved in the RECs, an asymptote value of the objective function is reached.

Effect of technology evolution (2035 forecast)

An evolution in efficiency and costs of fuel cell and hydrogen is expected in the coming years. Al-Hamed and Dincer [52] stated an efficiency of 60 % for solid oxide fuel cell (SOFC) based on LHV. The same value is stated currently in datasheet from Convion, a SOFC manufacturer [53].

For a 250 kW SOFC (electric-only system), Whiston et al. [54] stated a median cost of 1909 $/kW (1775 €/kW with a dollar/euro exchange rate of 0.93) with a production volumes of 4000 system per year in 2035. In 2050 a reduction to 841 $/kW is expected with a production volume of 10,000 systems per year.

Krishnan et al. [55] argued a mean value cost for alkaline and PEM

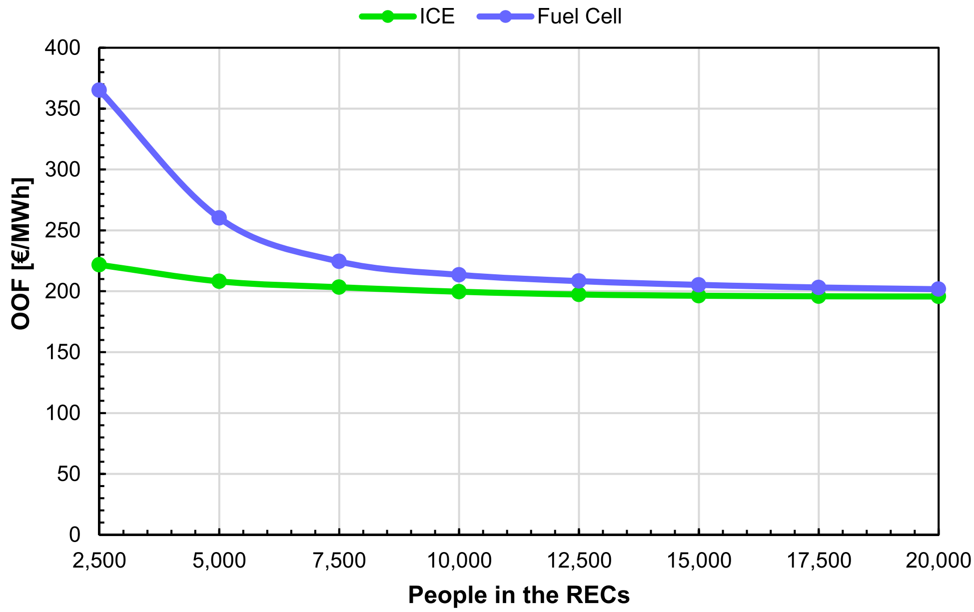

Fig. 6. Optimization objective function (OOF) as a function of RECs' size.

Table 4
Fuel cell and electrolyser data at 2035.

Parameter	Value	Ref.
Fuel cell capital cost [€/kW]	1775	[54]
Electrolyser capital cost [€/kW]	470	[55]
Fuel cell efficiency (on LHV)	60 %	[52,53]
Electrolyser efficiency (on LHV)	70 %	[40,55]

electrolyser at 2030 of 470 €/kW with an efficiency of 69 %, substantially equal to what is assumed in this study (70 %).

Considering the data as summarized in Table 4, not considering 40 % non-refundable loan for the CAPEX of hydrogen storage system (the current incentives is provided until 2026 [47]) and consequently with incentives tariff (*IT*) as in the following equation

$$IT = min\begin{cases} [80 + \max(0; 180 - zonal\ price)] €/MWh \\ 120\ €/MWh \end{cases} \quad (7)$$

the results of the optimizations are shown in the Fig. 7 considering the trend of optimization objective function (*OOF*).

The evolution of performances and costs of both fuel cell and electrolyser enables from 2035 the proposed model: starting from around 3000 people involved in the RECs the LCOE is smaller than annual mean selling price for electricity produced by UVAM in the seven market areas of Italy (211 €/MWh): optimization objective function (*OOF*) becomes negative.

In Fig. 8 net present value (NPV) and investment return time better explain the trends of the economics and in Fig. 9 the CAPEX breakdown of the main components of the system is shown.

A general overview of the facts and figures of the scenario with 10,000 people involved in the RECs is reported in Table 5. Beyond this

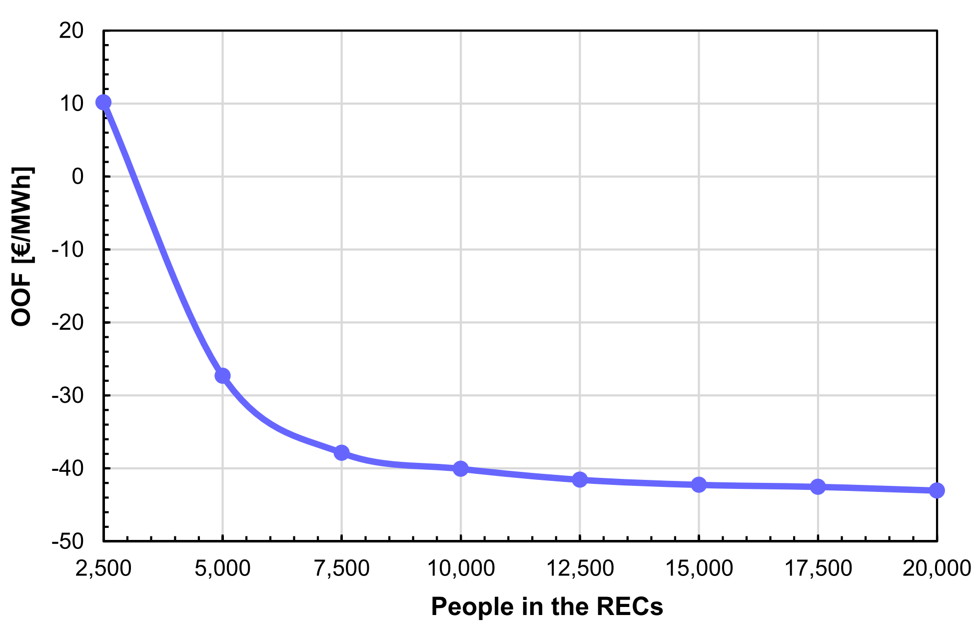

Fig. 7. Optimization objective function (OOF) (2035 forecast).

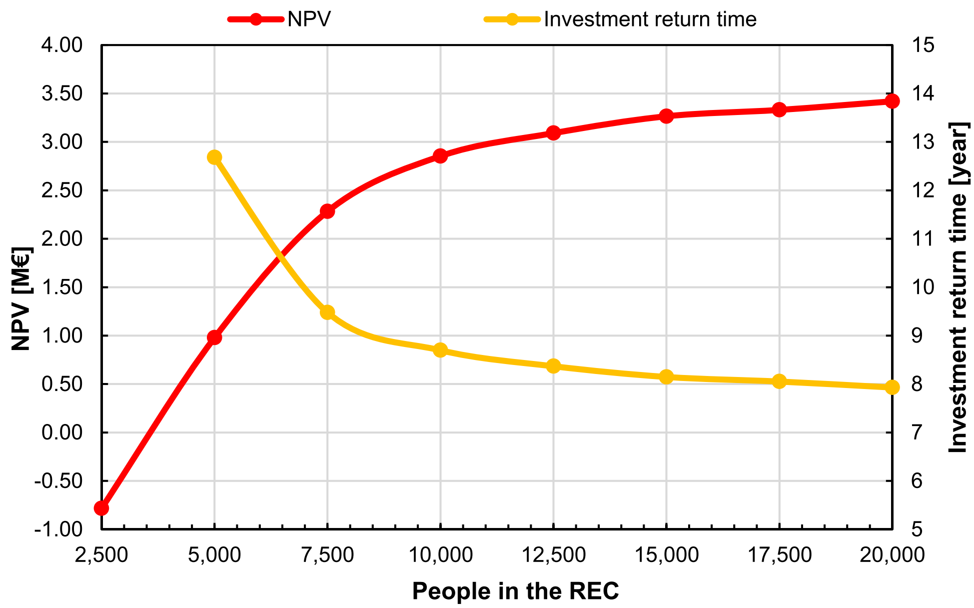

Fig. 8. Net present value and Investment return time (2035 forecast).

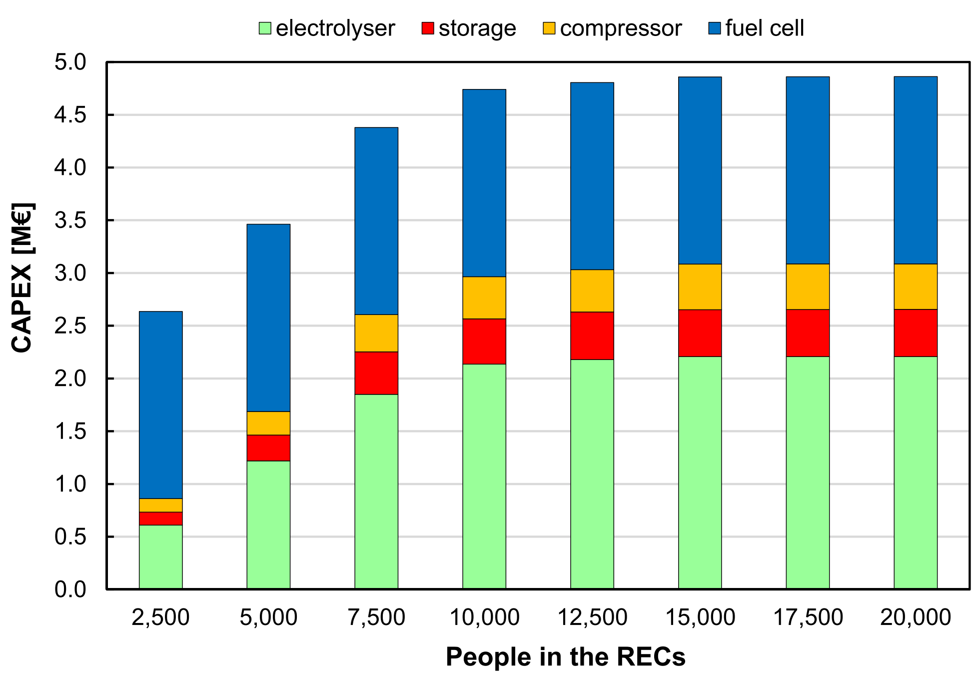

Fig. 9. CAPEX distribution (2035 forecast).

size both the increase in capital expenditure and economic performance are marginal: consequently, this size could be considered the most suitable to manage the smallest UVAM allowed by Italian regulation (1 MW) based on photovoltaic installed in residential RECs. In this case LCOE is equal to 171 €/MWh with a total CAPEX of 4.75 million euro.

Discussion

Based on the current costs of the hydrogen systems (electrolysers, FC and ICE), the proposed system appears to be economically unsustainable. Conversely, the projection of such economic values in 2035 makes the sustainability of the proposed scenario acceptable. In the latter case the proposed system, sized on 10,000 inhabitants participating to different RECs in the same primary HV/MV electrical substation, is the biggest one with a relevant marginal economic increasing. Photovoltaic generation in this system has an overall power of 18 MWp composed of many plants each one with a peak power less than 200 kWp; overall electrolyser power is 4.54 MW; a hydrogen compressor of 250 kW power assures the storage in a common high-pressure storage (200 bar) with a capacity of 838 kg of hydrogen starting from a 116 kg low-pressure storage (35 bar). Based on techno-economic evolution of electrolyser and fuel cell at 2035, LCOE of the latter case is 171 €/MWh for balancing service provider that manage the 1 MW UVAM. Considering an annual mean selling price for electricity in ancillary market of 211 €/MWh (2023 economic data) and a CAPEX of 4.75 million euro, net present value is 2.85 million euro and investment return time 8.7 years.

The proposed analysis is aimed at private entrepreneurs and managers of RECs, in particular in cases RECs have excess renewable

Table 5
Facts and figures with 10,000 people in the RECs.

Total users (domestic LV 3 kW users)	4762		Electric flows in the RECs		
Total people in the community	10,000		Renewable energy production	26,532	MWh/ year
				Shared energy	
Sizing			Shared energy for residential use	5422	MWh/ year
PV peak power	18.0	MWp	Shared energy for electrolyzes	11,987	MWh/ year
Electrolyzer nominal power	4.54	MW	Shared energy in H2 compression	669	MWh/ year
Fuel cell nominal power (UVAM)	1.00	MW	Total shared energy	18,079	MWh/ year
Compressor nominal power	250	kW	Renewable energy to the grid	8453	MWh/ year
Low pressure hydrogen storage	116	kg	Energy from the grid (residential use)	5880	MWh/ year
High pressure hydrogen storage	838	kg	Electric flows in the UVAM		
Total hydrogen storage	954	kg	Electricity to ASM	4714	MWh/ year
(based on LHV)	31.8	MWh	Electricity produced in warm-up	320	MWh/ year
			Total hydrogen consumption	251.7	ton/ year
ASM sessions and running hours			Equivalent hours at nominal power		
UVAM availability (due to H2 storage)	6682	hh/ year	Electrolyser	2638	hh/ year
Active market sessions (all 7 zones)	6505	hh/ year	Fuel cell	4861	hh/ year
UVAM active time (FC running)	4714	hh/ year	Load factor		
Number of UVAM warm-up	766		Electrolyser	30 %	
Annual warm-up time	587	hh/ year	Fuel cell	55 %	

production that is not consumed locally. The creation of a renewable hydrogen production and storage chain to serve the balancing of the national electricity grid could be a business of interest by 2035. In fact, the scenario will be technically feasible, compliant with regulatory Italian scenario and economically sustainable for create new companies in the field of decentralised electricity generation.

Batteries or more complex Power-to-X (PtX) plants [56,57] can be introduced to make the excess renewable energy produced in some RECs dispatchable in the TSO grid in ASM. However, these systems appear to present several intrinsic issues. Battery-based systems are unable to decouple power from stored energy and furthermore it is difficult to create configurations in which the energy input and output are on two different PODs (one for the DSO grid and one for the TSO one). More complex PtX systems producing (i.e.) ammonia or synthetic methane appear at present too expensive and not suitable to reach dimensions as small as those suitable for the plausible dimensions of RECs. Future studies may verify these considerations in more detail.

Conclusions

This study introduces an original business model based on a hydrogen producing company (H_2 company) and a balancing service provider in the Italian national electric grid that manage an UVAM (virtually aggregated mixed unit). In a high level of photovoltaic penetration area served by the same electrical primary substation (HV/MV substation) of the DSO grid, many renewable energy communities (RECs) integrate each one an electrolyser owned by H_2 company. The company produces hydrogen from excess of electricity generated in residential RECs powered by photovoltaic and stores hydrogen in a common high-pressure storage. Hydrogen stored is consequently sold to a balancing service provider that manage an UVAM of 1 MW based on hydrogen power plant that produce electricity in the ancillary service market feeding TSO grid, following awarding of daily auctions in the national electricity market.

The business model allows to aggregate and make dispatchable excess of renewables generated in a territory through REC and UVAM that represent innovative and flexible entities in the electric Italian market.

The purpose is to investigate by a techno-economic assessment the current and future economical sustainability of the business model in the Italian regulatory and market scenario, producing renewable hydrogen exploiting REC's incentives and using it to dispatch renewable electricity in the richest electricity market existing in Italy (ancillary service market) through UVAM project.

The main findings of the present study can be summarized as follows:

- the current regulatory framework in Italy allows the full realization from a legal perspective of the proposed scenario;
- the technological and cost maturity of the solutions currently available (electrolysers, fuel cells or internal combustion engines powered by hydrogen) does not allow present-day economic sustainability;
- currently Italian non-refundable loans for RECs established in municipality under 5000 inhabitants cannot compensate for the lack of economic maturity of the enabling technical solutions;
- the expected technical and cost evolutions for electrolyser and fuel cell in the coming years (by 2035) will allow economic sustainability to be achieved;
- in the assumed electrolyser and fuel cell evolution at 2035, considering a population greater than 3000 inhabitants aggregated in RECs in a high photovoltaic penetration condition (1.8 kWp/capita), the proposed business model is economically sustainable considering Italian electrical market at 2023.

In Italian regions with a likely wide development of RECs in the coming years, the proposed business model appears to be a valid alternative to reduce the impact of a high penetration of renewables on DSO grid, offering at the same time a solution for TSO grid balancing using renewable dispatchable energy.

CRediT authorship contribution statement

Giulio Raimondi: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Giuseppe Spazzafumo:** Writing – review & editing, Validation, Supervision.

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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