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Smart energy systems for renewable energy communities: A comparative analysis of power-to-X strategies for improving energy self-consumption

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ABSTRACT

Renewable energy communities (RECs) represent the new scheme for promoting the distributed renewable generation, which must be managed to maximise the local energy self-consumption. The aim of this paper is to assess and discuss strengths and weaknesses of small-scale sector coupling strategies in residential RECs by means of a comparative analysis of their applications. Different power-to-X strategies have been applied to twenty-seven REC configurations. The systems have been separately simulated by means of the EnergyPLAN software. Power-to-heat strategy turns out to be the most cost-effective solution to integrate the RES excess, however, its potential often is not enough to fully accommodate it. Power-to-vehicle has low infrastructure costs, but its limit depends on the electric vehicle penetration and citizens' participation. Exploiting the electric vehicle batteries is always more cost-effective than installing stationary batteries. The competitiveness of power-to-power is extremely linked to the REC electrification level. Power-to-gas is promising in high-RES excess conditions, but rarely represents the best solution due to current high electrolyser costs. The implementation of energy storage systems is crucial for improving the local self-consumption and the cross-sector integration is a better solution in energy, economic and environmental terms than focusing only on the electricity sector.

1. Introduction

The rapid deployment of renewable energy sources (RES) is taking place to meet international greenhouse gas emission (GHG) reduction targets. Conventional energy systems powered by centralised fossil fuel power plants are giving way to distributed energy systems based on decentralised renewable generation.

The EU Directive 2018/2001, also known as Renewable Energy Directive (RED II), formally introduced Renewable Energy Communities (RECs), an energy governance model to promote the distributed RES deployment and citizen participation in the energy transition process. RECs are legal entities allowing community members to collectively produce, manage, store, and sell renewable energy. The main purpose of RECs *"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"* [1].

Such an energy model should not only support the development of distributed generation, but also manage the system in order to maximise local energy self-consumption (SC) [2]. Indeed, numerous decentralised generation plants are not manageable by existing power grids. According to Ref. [3], current electricity networks can accommodate up to 40 % of electricity hailing from Variable RES (VRES).

The challenge of integrating VRES in distributed energy systems has been widely discussed in the recent years. That issue has been firstly investigated by means of electric batteries (EBs). Nevertheless, electrochemical storage systems are characterised by high costs [4] and significant environmental impact on the life cycle [5]. Thereby, the system flexibility cannot be efficiently provided by focusing only on the electricity sector, but must be pursued by exploiting synergies between sectors and integrating electricity, thermal and gas networks.

That concept is known in literature as the Smart Energy Systems (SES) approach, proposed by Lund et al. [6], in order to overcome the single-sector approach towards a holistic and integrated one. According to Ref. [7], "*a Smart Energy System is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system*".

Several works demonstrate the benefits of exploiting different cross-sector interconnections to integrate the VRES generation [8]. In literature, the preposition "Power-to" is used to indicate the conversion of

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renewable electricity into other energy carriers [9]. Furthermore, Power-to-X (PtX) strategies consist of energy carrier conversions to efficiently use available energy storage technologies. There is no unique definition of the Power-to-X concept, and several meanings can be found in literature.

In most of scientific works [10–12], the use of PtX is limited to the concept of Power-to-Gas (PtG), i.e. the conversion of electricity into hydrogen and in other synthetic products (also known as Power-to-fuels or Power-to-Liquid, when the fuel is in a liquid state). In other studies [13–15] the PtX concept is used to denote both PtG and Power-to-Heat (PtH) applications. The latter is the conversion of electricity into thermal energy. Others [16–18] extend the concept to all the electricity conversion in energy carriers, including the final reconversion into electricity (Power-to-Power) or the application to the mobility sector (Power-to-Vehicle or Power-to-Mobility). In order to identify a unique definition, the Power-to-X concept can be intended as *the general conversion of renewable electricity into different energy carriers or applications*.

By the wide deployment of distributed generation plants, the SES approach and the PtX strategies become of utmost importance also on a local scale in order to limit the electricity injection into the local power grid.

The aim of this paper is to assess and discuss strengths and weaknesses of small-scale PtX applications in residential RECs. The state-of-art of Power-to-Power (PtP), Power-to-Gas, Power-to-Heat and Power-to-Vehicle (PtV) systems has been reviewed.

Furthermore, the PtX strategies have been applied to a REC in order to analyse their viability to maximise the energy SC, mitigate GHG emissions and reduce community annual costs. The comparison between the four PtX strategies has been carried out by investigating 27 REC configurations in order to generalise as much as possible the analysis. Moreover, this paper contributes to demonstrate the need for the SES approach in distributed energy systems.

2. Power-to-X systems

The distributed RES deployment will go hand in hand with the energy storage systems' one. Several solutions for converting the RES excess have been investigated in the recent years. To model and simulate different energy scenarios, some of the most common PtX strategies have been considered. To identify suitable smart energy storage solutions for RECs, the state-of-art of small-scale PtX applications has been reviewed. In detail, an overview of PtG, PtP, PtV and PtP systems is presented below.

2.1. Power-to-Gas

Converting electricity into hydrogen by means of water electrolysis represents a viable solution for balancing local power grids [19]. The potential role of PtG systems for storing the RES excess and mitigating renewable fluctuations in distributed energy systems has been widely analysed in literature [20,21]. Fonseca et al. [22] reviewed more than one hundred studies investigating the potential hydrogen role in distributed energy systems. According to them, a wide variety of scales was considered for PtG applications, nevertheless, only a few case studies assessed the hydrogen role in neighbourhoods and residential complexes.

The role of hydrogen for balancing power grids by means of fuel cells has been investigated in literature [23]. Nevertheless, hydrogen is not the best option for balancing VRES on electricity networks due to the low round trip efficiency of Power-to-Gas-to-Power process [24]. More interesting is the hydrogen application for other purposes not correlated to the electricity generation [25].

It can be used for producing alternative fuels, such as synthetic natural gas, methanol, ammonia and DME (dimethyl ether) [26]. However, the production of electro-fuels requires large-scale reactors, representing a barrier for implementation in small-scale energy communities [27].

Hydrogen can instead be a vector for the transport sector decarbonisation [28]. However, nowadays, hydrogen refuelling stations, as well as hydrogen vehicles, are not widespread.

A viable solution for small-scale applications is the blending of hydrogen with natural gas (NG). For low volume fractions, there are no significant changes in the main parameters of both gas infrastructure and gas-driven end-use devices [29].

This solution also has the advantage of not requiring a dedicated infrastructure, but exploits the current gas infrastructure, which is widespread in some countries. Furthermore, blending presents far fewer safety risks than classical hydrogen transport and storage solutions [30].

2.2. Power-to-Heat

Power-to-Heat strategy is the flexible conversion of power into thermal energy, by means of heat pumps (HPs) either for heating or cooling purposes.

Compression HPs are commercial devices producing heat in an efficient and cost-effective manner. PtH systems can be considered promising solutions for integrating RES excess both by flexible demand and thermal energy storage (TES) [31]. TES consisting of hot water tanks is a simple and economical solution for storing excess renewable energy [32].

The potential flexibility provided by PtH systems is correlated to the HP size, the TES size, the thermal demand and its profile [33]. Therefore, often PtH applications present limits due to endogenous factors.

Several works analyse HPs in residential applications for providing system flexibility [34]. Furthermore, many studies investigate the local RES integration focusing on the energy self-consumption [35].

The PtH strategy can be applied in a centralised or decentralised manner depending on the thermal infrastructure [36]. Indeed, each building can be supplied by individual HPs, or several buildings can be supplied by a district heating (DH) network. The fourth generation of DH (4GDH), i.e. a low-temperature smart thermal network, allows for integrating renewable generation in energy districts, decarbonising thermal demand, reducing thermal losses and providing a cost-effective solution for storing intermittent generation [37].

2.3. Power-to-Vehicles

In order to decarbonise the transport sector, the wide deployment of electric vehicles (EVs) is crucial [38]. EVs can represent a means for balancing power fluctuations due to VRES generation [39]. The integration of EVs in future smart energy systems with high RES share have been widely investigated in literature [40]. Furthermore, several works assessed the topic of EV charging management [41]. In the absence of coordinated charging, electric vehicles represent an inflexible demand that can create further uncertainty in renewable energy systems. The role of an aggregator for managing electric vehicle charging is necessary to coordinate generation and demand [42].

Smart management of electric vehicle charging is identified in the literature by many names, such as smart charging, Vehicle-1-Grid or Power-to-Vehicle.

In general, that strategy consists of varying the charging scheduling by shifting the demand over time and modulating the charging power according to renewable generation [43].

Vehicle-to-grid (V2G) systems, meanwhile, consist of a two-way flow between vehicles and the electricity grid [44]. Vehicles provide their electric batteries as a storage system for renewable generation and supply energy to the grid when the intermittency of renewables is needed [45]. Therefore, EVs can become suppliers and balance the local energy system [46].

The technical infrastructure is not excessively expensive, as it consists of a computer system for energy flow management in addition to the charging stations [47].

Table 1
Characteristics and electricity demand of REC and dwelling archetypes.

Dwelling Archetype	Number of dwellings	Inhabitants (n° of people)	Surface (m^2)	Annual Electrical Consumption (MWh/year)
A	50	2	60	0.95
B	50	3	67	1.91
C	50	4	134	2.53
D	50	3	137	2.5
Energy Community	200	600	19,900	394.4

Table 2
Heating, cooling and DHW demand of REC and dwelling archetypes.

Dwelling Archetype	Annual heating demand (MWh/ year)	Annual cooling demand (MWh/ year)	Annual DHW demand (MWh/ year)
A	4.22	3.02	1.06
B	4.71	3.37	1.13
C	9.42	6.74	1.89
D	9.63	6.89	1.92
Energy Community	1398.9	1000.9	300.2

In the case of bi-directional flows, the overall costs increase due to the management system complexity. Furthermore, even more complex scheme have been analysed such as vehicle-to-vehicle systems, i.e. the transfer of energy from an EV to another [48].

The main barrier to such a strategy is the EV owners' participation, who need to make their vehicles available for a longer period than just recharging. Furthermore, in the case of V2G strategy, the two-way flow and numerous charge and discharge cycles lead to rapid degradation of EV batteries [49].

2.4. Power-to-Power

With the Power-to-Power concept, it can be generally indicated a storage system providing power as output [9]. PtP systems convert electricity into chemical or mechanical energy for storing and then it is reconverted into electricity. At national scale, the most widespread PtP applications regard pumped hydro storage. Also compressed air energy storage can be counted as PtP system, nevertheless, that technology is rarely used.

The most mature PtP technology for small scale applications are electric batteries. Rechargeable electrochemical batteries, also called second batteries, are chemical energy storage systems concerning different commercial technologies. Of these, lithium-ion batteries are the most widely used for small-scale stationary storage, due to their high energy density, high round-trip efficiency and long lifetime [50]. Currently, their costs are very high, but they are expected to decrease rapidly in the coming years [51].

EBs can help the integration of VRES generation enhancing the local electricity self-consumption and their role is important in providing various services for balancing and managing electrical distribution networks [52]. However, self-discharge is a problem for most electrochemical batteries, which limits their role to short-term storage applications and their costs is currently not competitive with other storage solutions [53]. Furthermore, their replacement due to their short lifespan leads to problems of chemical disposal and material consumption that result in considerable life-cycle environmental impact [54].

3. Material and methods

The aim of this paper is to assess and discuss strengths and weaknesses of small-scale PtX applications in residential RECs. The application of PtX strategies to a case study, consisting of ten buildings and two hundred flats has been investigated. The case study has been modelled considering electricity, heating, cooling, and transport demand.

A preliminary analysis comparing a conventional and a smart energy system layout has been carried out in order to investigate the ability of the two systems to integrate the renewable generation. Furthermore, from this analysis, three photovoltaic (PV) configurations in the smart scenario have been chosen for assessing the PtX strategies under different RES excess conditions.

PtP, PtH, PtG and PtV systems have been separately simulated by means of EnergyPLAN. In order to compare each other the different strategies, a correlation between the energy self-consumption and the REC annual costs, hailing from the energy storage systems size variations, have been made. In such a way, the best strategy, for each SC level can be easily identified. The four strategies have been also assessed in terms of annual avoided CO_2 emissions.

Furthermore, in order to widen and generalise the analysis, the EV penetration and the Power-to-Heat ratio (PTHR) have been varied, so that twenty-seven REC configurations have been studied. The PTHR can be defined as the ratio between the annual electricity demand and the annual heating demand.

3.1. EnergyPLAN

EnergyPLAN is an energy system analysis tool, developed at Aalborg University, for modelling and simulating future energy systems characterised by large RES penetration [55]. It is a deterministic input/output tool using an hourly time-step over the analysis. EnergyPLAN takes into account different energy sectors, including electricity, heating, cooling, transport, and industry. Additionally, several conversions between energy carriers and numerous renewable and conventional technologies can be simulated.

One of the most important advantages of EnergyPLAN is the very short computational time allowing the coupling with different tools in order to perform a large number of energy system simulations [56]. EnergyPLAN has been applied at quite different scales. Connolly et al. [57] analysed the decarbonisation of the European Union by 2050. Furthermore, the main scale investigated by means of EnergyPLAN is the national level [58]. Nevertheless, several studies applied it to cities [59], municipalities [60], islands [40] and districts [61] analysis.

3.2. Case study

The case study is a residential REC located in Rome, consisting of ten buildings and two hundred flats. The REC model has been built referring to the study of Mancini et al. [62] for the electrical loads and the dwelling archetypes definition. Their work presents a methodology for estimating the load profile of a residential cluster by combining experimental and statistical approaches. Moreover, average hourly loads, divided by working, pre-holiday and holiday days for each month, have been defined for fourteen dwelling archetypes by means of a monitoring action over the years 2018 and 2019. Four archetypes have been considered for the REC model assessed in the present work. Their main characteristics have been reported in Table 1.

Heating and cooling demand have been defined in accordance with the work of Mancini et al. [63], which defines average energy performance (EP) indicators for a residential complex in Rome. The EP indicators for heating (EPh) and cooling (EPc) are equal to 70.3 kWh/m^2yr and 50.3 kWh/m^2yr, respectively. The domestic hot water (DHW)

Table 3
Energy demand of transport sector for REC in the conventional scenario.

Vehicle type	persistence of vehicle fleet (%)	Transport demand (km/year)	Fuel/Electricity demand (MWh/year)
Petrol	49.8%	1,533,840	935,7
Diesel	39.9%	1,228,920	607.6
Electric	1.5%	46,200	8.2
Gas	8.8%	271,040	152.4
Energy Community	100%	3,080,000	

Table 4
Energy demand of transport sector for REC in the smart scenario.

Vehicle type	persistence of vehicle fleet (%)	Transport demand (km/year)	Fuel/Electricity demand (MWh/year)
Petrol	25.3%	779,240	475
Diesel	20.3%	625,240	308.5
Electric	50%	1,540,000	272.6
Gas	4.4%	135,520	77.4
Energy Community	100%	3,080,000	

demand has been computed according to the Italian standard UNI/TS 11300 [64]. The heating, cooling and DHW demands for dwelling archetypes and the overall values for the REC have been summarised in Table 2.

Hourly load profiles of heating, cooling and DHW demands have been considered on the basis of the data made available by the Hotmaps Project [65]. The Hotmaps open data repositories provide aggregated hourly load profile on NUTS 2 level for different energy sectors. In such a way, the REC's annual demands have been distributed on hourly basis. In order to model the transport demand, the data of transport in Rome have been considered in accordance with the Roman mobility report [66]. Average per capita car movements are equal to 1.07 movements per day and average distance of single movement is equal to 13.1 km. The REC is composed by 600 people, thereby the total transport demand associated to the REC's citizens is equal to 3,080,000 km/year. In 2020, the car fleet in Rome is composed mainly by petrol and diesel vehicle. EVs represent only the 1.5% of the Roman car fleet. The shares of vehicle types have been used to build the local transport demand for the residential REC. In Table 3, the energy demand associated to the transport sector for REC in the conventional scenario have been summarised. The hourly profile of transport demand has been modelled according to Ref. [67]. In that work, the authors present a time series with a high temporal resolution describing the traffic profile in the city of Turin.

3.3. Conventional energy system

The conventional scenario represents a common energy system of an Italian residential district. Electricity demand is met by power grid, whilst NG boilers supply heating and DHW demand. As regards the cooling load, it is generally guaranteed by the use of air-to-air heat pumps. Furthermore, the car fleet has been presented in Table 4, according to the average distribution of vehicle types in Rome. A boiler for each building has been considered, furthermore cooling demand is supplied by individual devices for each flat. The conventional energy system configuration has been depicted in Fig. 1.

3.4. Smart energy system

The smart energy system configuration envisages the wide electrification of energy end-uses. It includes air-to-water heat pumps for supplying heating, cooling and DHW demands. A reversible HP for each building and additional HPs for DHW have been considered.

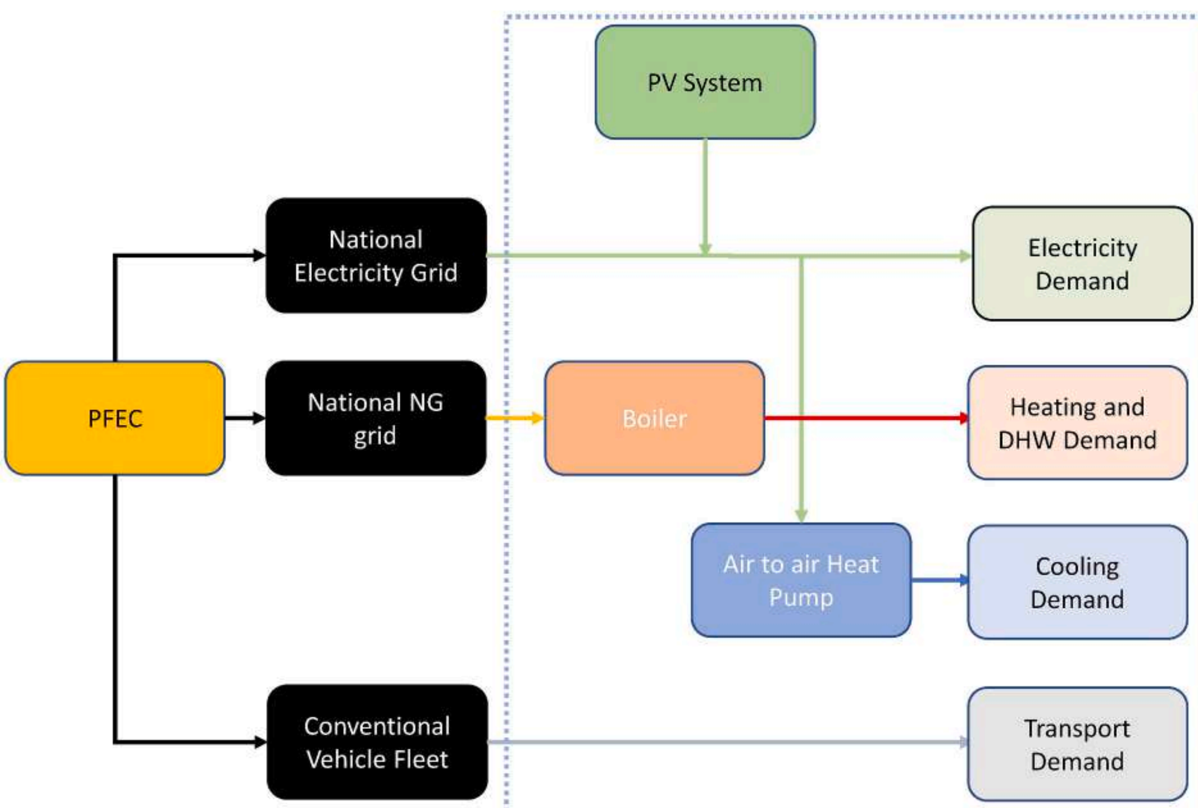

Fig. 1. Conventional energy system configuration of a renewable energy community.

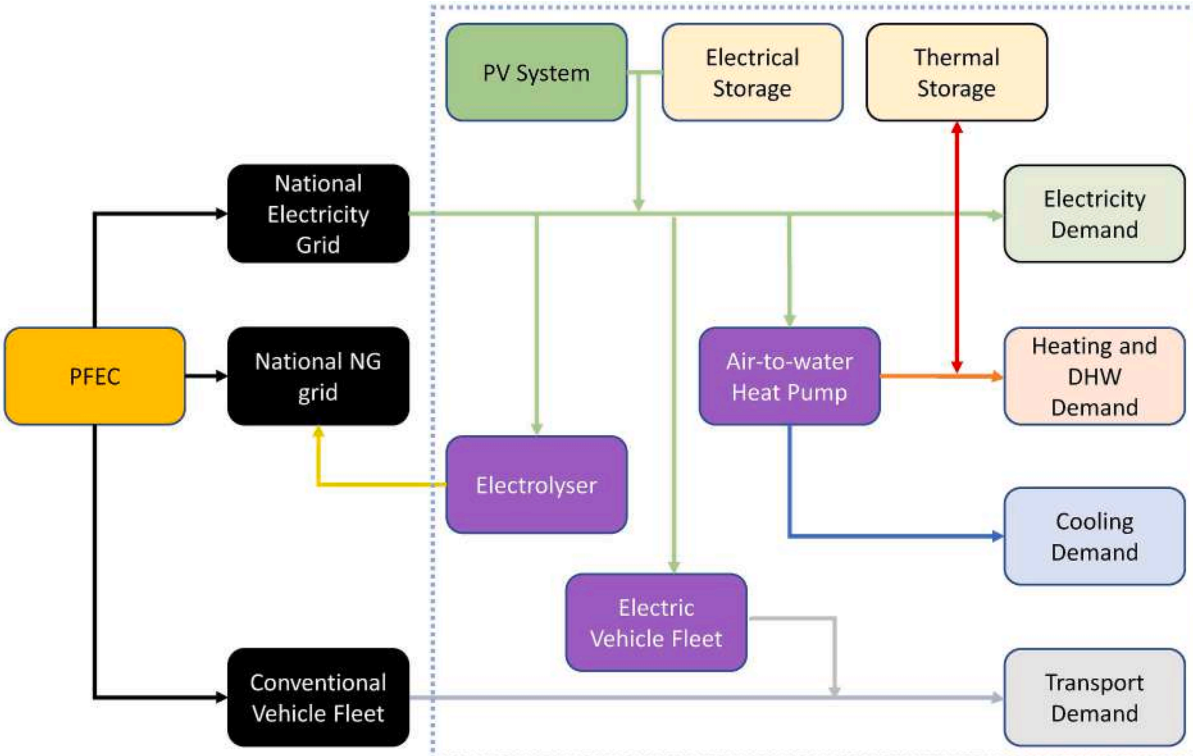

Fig. 2. Smart energy system configuration of a renewable energy community.

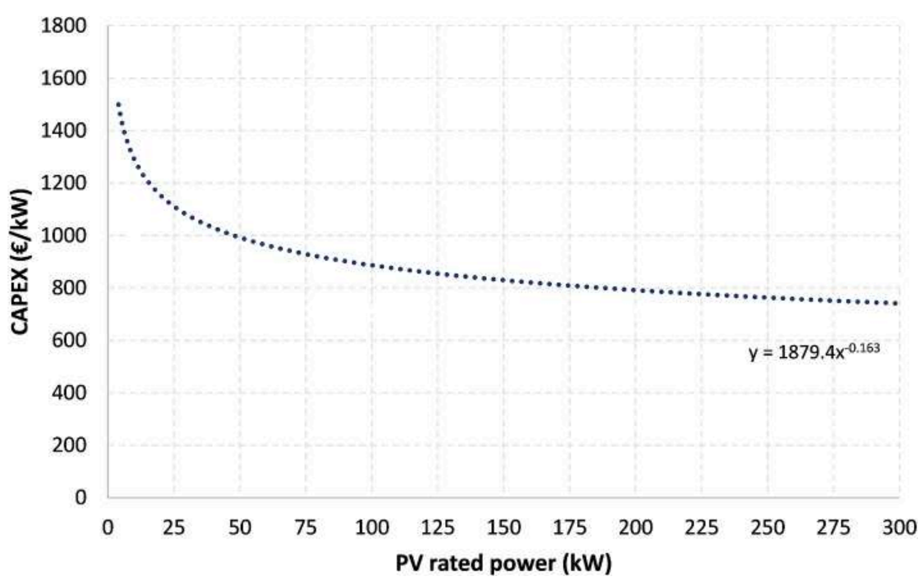

Fig. 3. PV specific cost curve [72,73].

Furthermore, the EV share has been enhanced up to 50% of the REC's car fleet. In Table 4, the energy demand of transport sector for REC in the smart scenario have been summarised.

In both conventional and smart energy systems, the integration of a PV plant has been analysed. Furthermore, several PtX options have been individually implemented in the smart scenario for converting and storing the RES excess.

- Traditional PtP system has been modelled with Lithium-ion batteries. The analysis has been carried out by changing the batteries array capacity.
- PtH strategy consists of exploiting a thermal energy storage (TES) system for converting the RES excess in thermal energy by means of heat pumps and storing it into hot water tanks. For that system, the parametric analysis has been carried out by enlarging the TES's size.
- PtG system consists of low temperature electrolysers for converting electricity into hydrogen. Thereafter, hydrogen is injected into the gas grid by means of mixing devices. A remuneration for hydrogen injected, equal to the energy price of NG for residential users, has been considered. PtG strategy has been implemented by varying the electrolysers' rated power input.

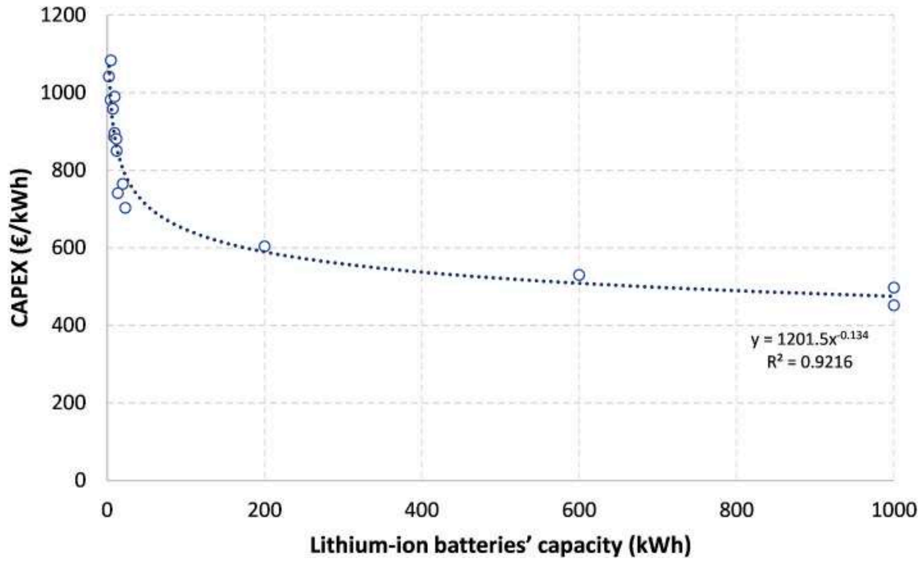

Fig. 4. Lithium-ion batteries' specific cost curve [32].

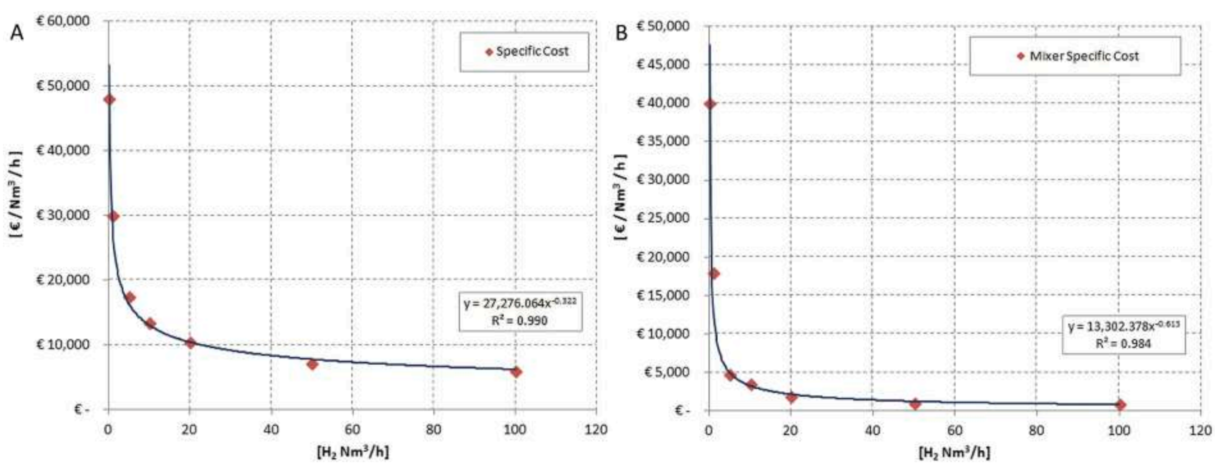

Fig. 5. Specific cost curve of Electrolysers (a) and Mixers (b) [74].

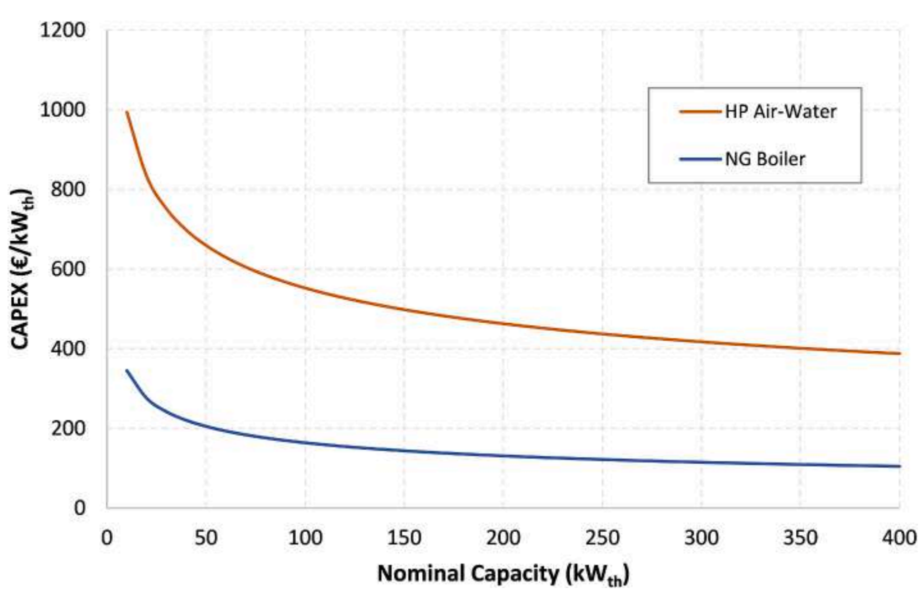

Fig. 6. Specific cost curve of HP Air-to-Water and NG boiler [76,77].

Table 5
Assumptions on O&M costs and lifetime for the system's components.

Component	O&M costs (% of INV)	Lifetime (years)	Ref.
NG Boilers	6.25%	20	[79]
Air-to-Air HPs	9.55%	10	[79]
Air-to-water HPs	5.84%	15	[79]
PV plant	1.58%	25	[80, 81]
Li-ion batteries	2%	15	[82, 83]
ALK electrolysers	2%	20	[84]
TES	0.7%	25	[79]
Dumb EV charge infrastructure	1%	20	[85]
Smart EV charge infrastructure	1%	20	[85]

Table 6
Energy prices for end-users.

Energy vector	Unit	Price
Electricity	€/MWh	184
NG from gas grid	€/MWh	86
Petrol	€/l	1.57
Diesel	€/l	1.41
LPG	€/l	0.71

Table 7
Thermal plants' size and average efficiency for both conventional and smart scenarios.

Scenario	Component	Rated Power (kW_{th})	Efficiency/ COP	Ref.
Conventional	NG Boilers	96	0.92	[71]
	Air-to-Air HPs	2.5	2.7	[90]
Smart	Air-to-water HPs for heating and cooling	88	3.07	[91]
	Air-to-water HPs for DHW	10	3.38	[91]

Table 8
Technical assumptions for the system's components.

Component	Parameter	Unit	Value	Ref.
PV plant	Annual producibility	kWh/kW/yr	1544	[92]
Li-ion batteries	Round trip efficiency	%	90	[93]
ALK electrolysers	Efficiency (LHV)	%	65	[94]
EV charge infrastructure	Charging efficiency	%	95	[85]

Table 9
Assumptions of specific vehicle consumption sorted by vehicle type.

Vehicle type	Specific Vehicle consumption	
	Unit	Value
Petrol	l/100 km	5.6
Diesel	l/100 km	4.9
Electric	kWh/100 km	11.5
Gas	kg/100 km	3.1

- Finally, PtV system includes the smart charge of EVs, to provide demand-side flexibility. EnergyPLAN controls the charging scheduling by varying time and power in order to balance renewable generation and integrate local excess. The strategy has been implemented by varying the share of electric vehicles participating in the smart charge scheme. Additional costs related to the charging infrastructure implementation have been externally computed.

The smart energy system configuration along with all the potential PtX strategies has been depicted in Fig. 2.

All the simulations have been carried out by means of EnergyPLAN. The software allows to model all the strategies by changing the computational variables described above.

3.5. Energy, environmental and economic indicators

For applying properly EnergyPLAN to a grid-tied REC, the electricity off takes through the community boundaries must be assessed according to the Italian network characteristics. The calculation of energy and environmental parameters has been carried out according to the methodology in Ref. [68]. The primary fossil energy factor of national grid has been computed according to Equation (1).

$$f_{nr,el\ grid} = \frac{1 - \%RES_{el}}{f_c * \eta_{th,el}} \tag{1}$$

where:

- $f_{nr,el\ grid}$ is non-renewable primary energy factor associated to the electricity grid.
- $\%RES_{el}$ is the average renewable energy share of the national electrical grid, which is equal to 38.08% for the Italian energy system, in 2020 [69].
- $\eta_{th,el}$ is the average efficiency of the national thermal power plants, equal to 0.422 [70].
- f_c is the is the correction factor for grid losses, in accordance with the Commission Delegated Regulation (EU) 2015/2402 of 12 October 2015, which reviews harmonised efficiency reference values for separate production of electricity and heat in Europe [71].

Thereby, the Primary Fossil Energy Consumption associated with the electricity consumption ($PFEC_{EL}$) can be defined according to Equation (2).

$$PFEC_{EL} = f_{nr,el\ grid} \bullet EL_{imp} \tag{2}$$

where EL_{imp} is the imported electricity.

In such a way, the REC Primary Fossil Energy Consumption (PFEC), expressed by MWh/yr, can be easily calculated by adding the factors related to fuels consumption and the imported electricity, according to Equation (3).

$$PFEC = PFEC_{FUELS} + PFEC_{EL} \tag{3}$$

$PFEC_{FUELS}$ is the sum of transport fuels and NG consumption from the gas grid and it is one of the EnergyPLAN output. Similarly, the emission factor of electricity consumption from national power grid can be defined as follows:

$$f_{e,el,grid} = \frac{\left(1 - \%_{RES,el}\right) * f_{e,th,el}}{f_c} \tag{4}$$

where $f_{e,th,el}$ denotes the average emission factor of national thermal power plants, which is equal to 444.4 kg_{CO2}/MWh_{el} [70]. Thereby, the annual CO_2 equivalent emissions due to the electricity consumption ($CO_{2eq,EL}$) can be defined in accordance with Equation (5).

$$CO_{2eq} = f_{e,el\ grid} \bullet EL_{imp} \tag{5}$$

Furthermore, the REC annual CO_2, eq emissions (CO_{2eq}), expressed by t_{CO2}/yr, can be computed by using Equation (6).

$$CO_{2eq} = CO_{2eq,FUELS} + CO_{2eq,EL} \tag{6}$$

As the energy self-consumption arising from PtX systems is the

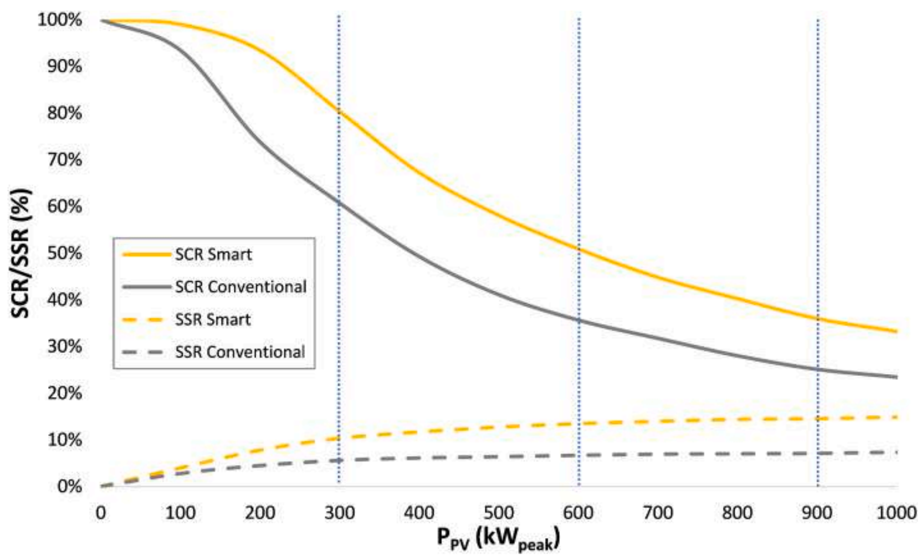

Fig. 7. SCR and SSR vs. P_{PV}; blue lines represent the scenarios, in terms of PV power, chosen for the analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

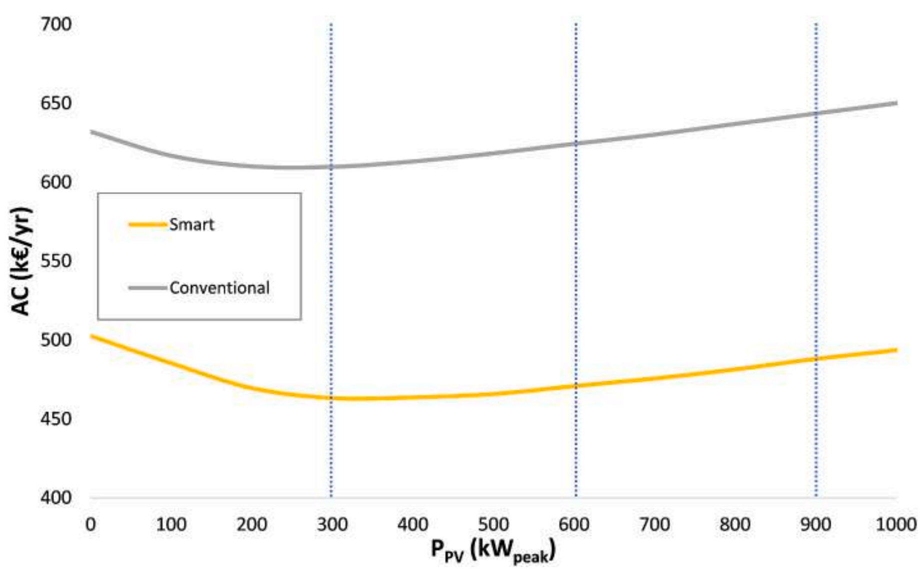

Fig. 8. ACs of REC vs P_{PV}; blue lines represent the scenarios, in terms of PV power, chosen for the analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

objective of this work, a key performance indicator has been used to assess that issue. The Self-Consumption Ratio (SCR) can be defined as the ratio between the renewable energy self-consumption (RE_{SC}) and the overall RES production over the year (RE_{PV}).

$$SCR = \frac{RE_{SC}}{RE_{PV}} \tag{7}$$

Furthermore, an additional indicator can be defined to properly evaluate the REC electrical self-sufficiency. That indicator is useful especially for assessing the RES penetration in the energy system in the preliminary analysis. The Self-Sufficiency Ratio has been defined as the ratio between the E_{SC} and the annual REC's primary energy consumption (PE_C).

$$SSR = \frac{RE_{SC}}{PE_C} \tag{8}$$

In addition, the PV factor (f_{PV}), which is expressed by the ratio between the annual energy PV production and annual REC's electricity need (EL_d), has been considered.

$$f_{PV} = \frac{RE_{PV}}{EL_d} \tag{9}$$

For evaluating the PtX strategies economic effectiveness, the annual costs (ACs) borne by RECs have been assessed. EnergyPLAN includes the economic evaluation and the AC calculation by considering energy vectors purchase (C_{EP}), investments costs and operation and maintenance ($C_{O\&M}$) costs. The investment costs calculation has been implemented accounting for the variability of Initial Capital Expenditure (CAPEX) by changing the plants' size.

ACs, expressed by €/yr, can be defined according to Equation (10).

$$AC = CAPEX \bullet crf + C_{O\&M} + C_{EP} \tag{10}$$

Here, *crf* is the capital recovery factor, which can be computed in accordance with Equation (11).

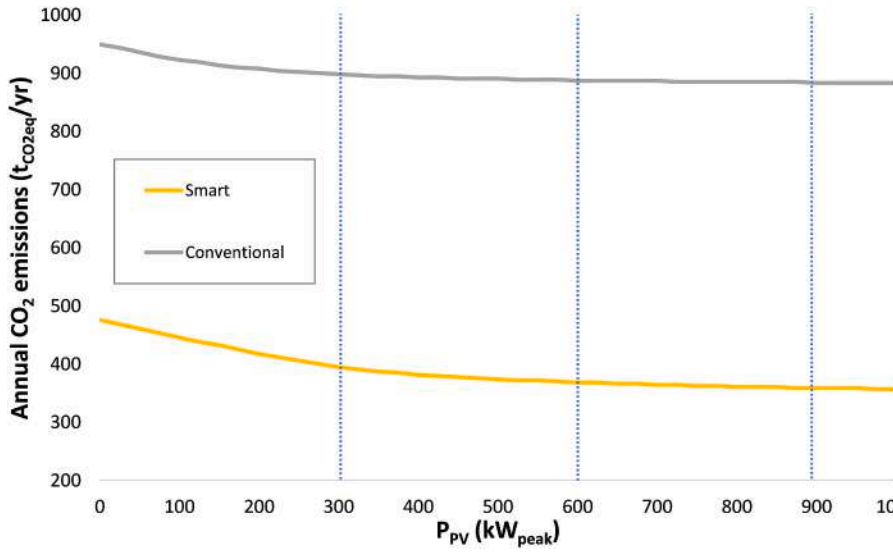

Fig. 9. Annual CO_{2eq} emissions of REC versus P_{PV}; blue lines represent the scenarios, in terms of PV power, chosen for the analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

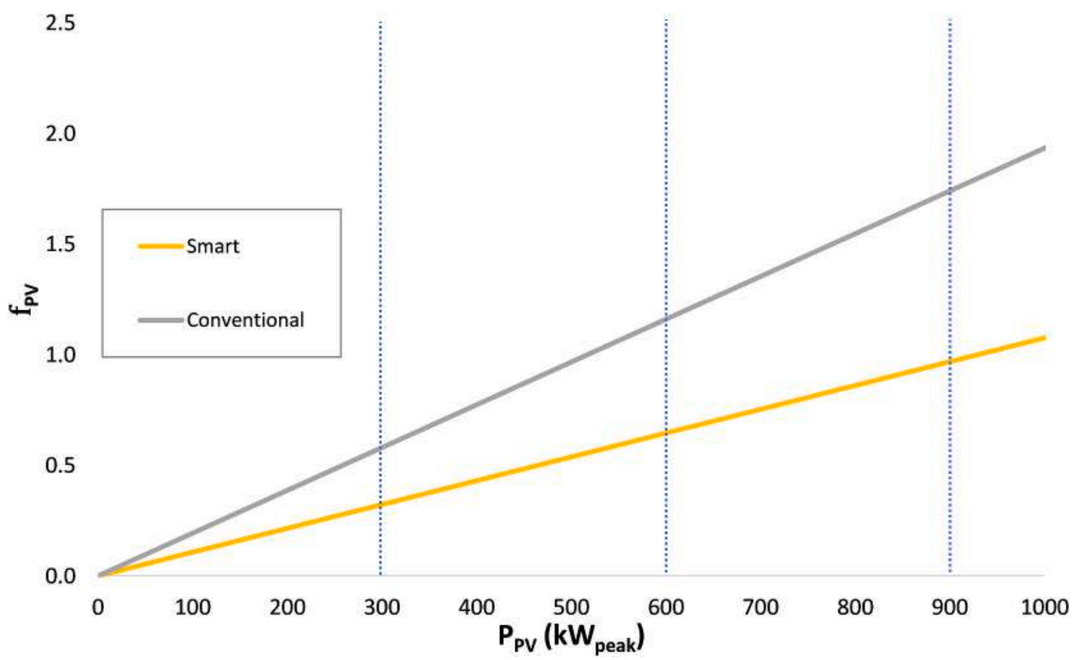

Fig. 10. f_{PV} versus P_{PV}; blue lines represent the scenarios, in terms of PV power, chosen for the analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 10
Main parameters of the PV scenarios chosen for the simulations.

Value	Unit	Scenario 300	Scenario 600	Scenario 900
PV size	kW	300	600	900
Annual RES production	MWh/year	73.5	147	220.5
f_{PV}	–	0.33	0.65	0.98
SCR	–	0.80	0.51	0.36
SSR	–	0.10	0.12	0.15

$$crf = \frac{i \bullet (1+i)^{\tau}}{(1+i)^{\tau} - 1} \tag{11}$$

where, i is the interest rate of investments and τ is the lifetime.

3.6. Technical and economic assumptions

To assess the CAPEX related to the main technologies applied in the present study, cost curves defining the unit investment cost versus the plant size have been used. In so doing, the size effect on the technologies' CAPEX has been considered. The PV CAPEX curve has been developed in accordance with Ref. [72] and applied in Ref. [73]. That curve has been depicted in Fig. 3.

The lithium-ion batteries' CAPEX curve has been defined according to Ref. [32] and depicted in Fig. 4.

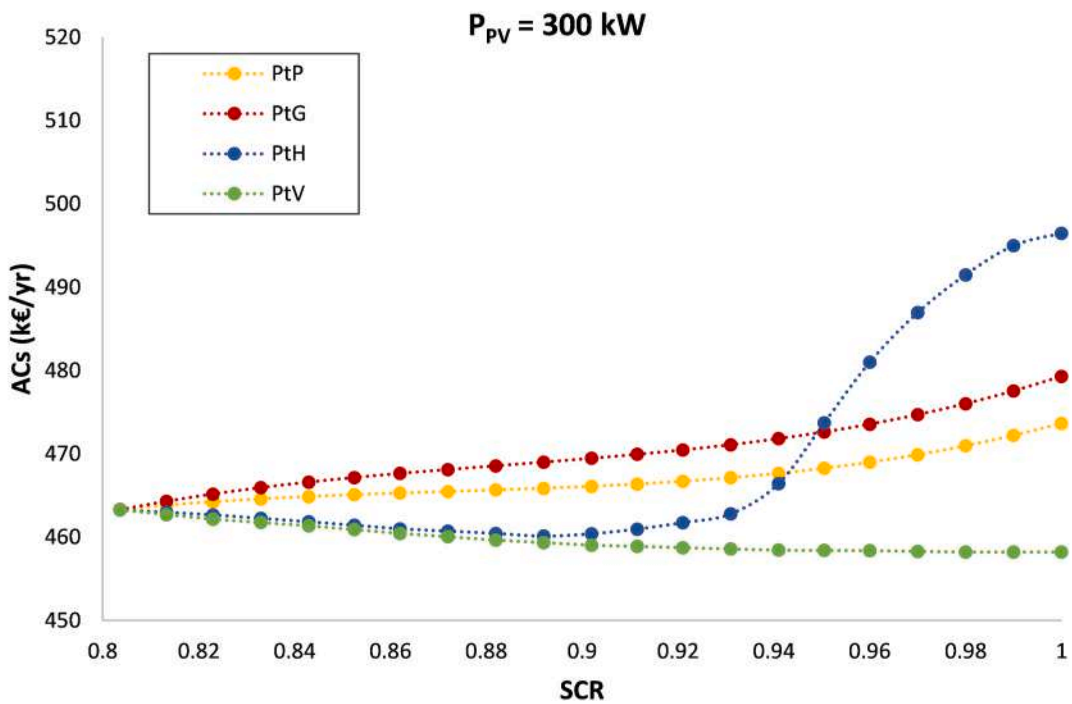

Fig. 11. SCR versus ACs in the scenario with P_{PV} equal to 300 kW.

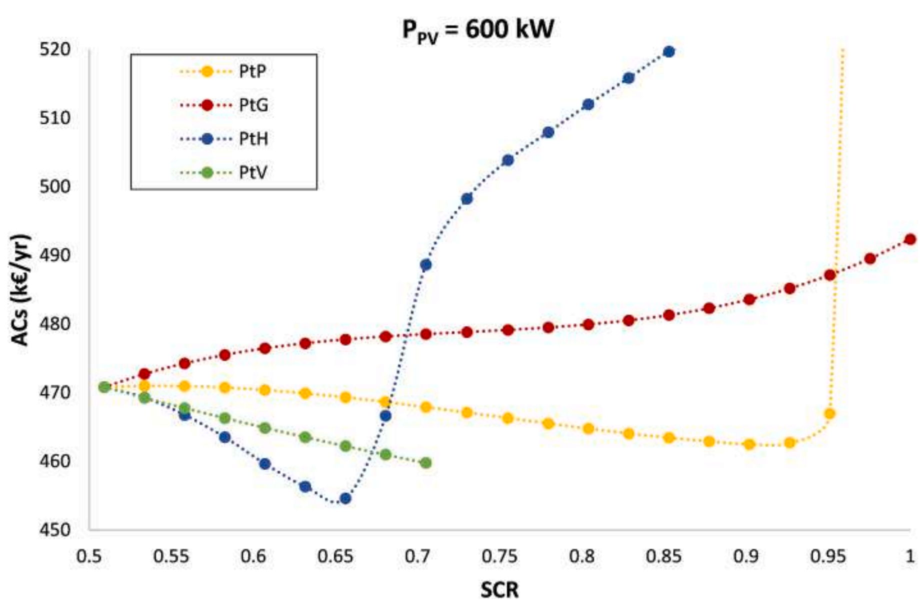

Fig. 12. SCR versus ACs in the scenario with P_{PV} equal to 600 kW.

Specific cost curves for alkaline electrolysers and mixing devices has been developed in Ref. [74] and are reported in Fig. 5.

In order to assess the installation cost of TES, Martínez-Lera et al. [75] proposed a specific cost function depending on the storage volume.

$$CAPEX_{TES} = 4042 \bullet V^{0.506} \tag{12}$$

Furthermore in Refs. [76,77], specific cost curves of air-to-water HPs and gas boilers have been developed. The curves have been depicted in Fig. 6.

According to Ref. [78], the investment cost for each charging station, characterised by a peak power of 11 kW, is equal to 1200 € and the further costs for installing the smart charge option are equal to 1500 €.

The assumptions on O&M costs and lifetime of the main components are outlined in Table 5.

The final energy prices for residential users have been fixed in accordance with Ref. [86] and presented in Table 6.

Some technical assumptions have been made in order to develop the analysis.

Electric vehicles have been modelled considering a maximum charging power and a vehicle capacity for each vehicle equal to 85 kW and 42 kWh, respectively [87]. Furthermore, the maximum power for each charging station has been considered equal to 21 kW [78].

The electricity used for producing hydrogen is considered as self-consumed energy although the hydrogen may not be consumed within the community once it is injected into the gas grid. Indeed, in literature [88], the issue of self-consumption concerns the need to locally use

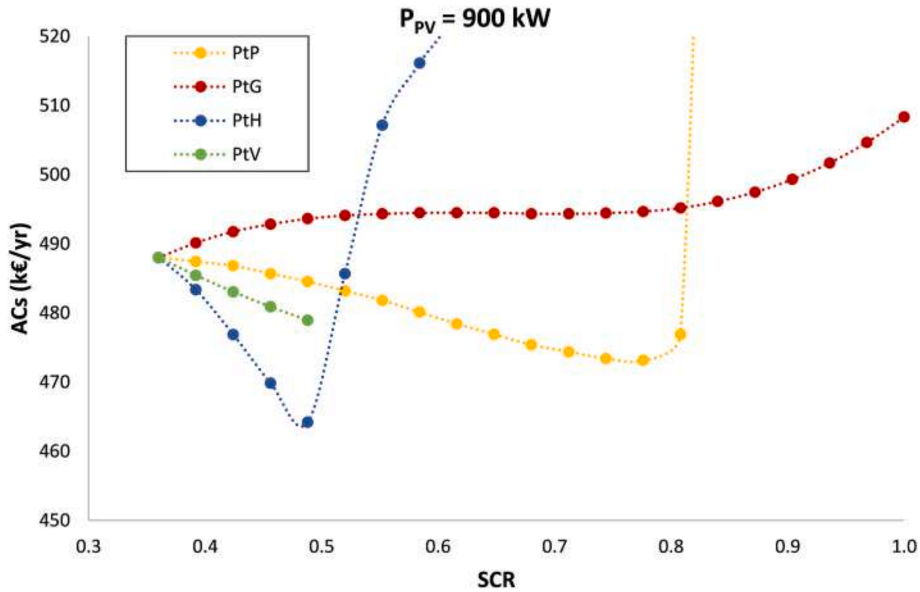

Fig. 13. SCR versus ACs in the scenario with P_{PV} equal to 900 kW.

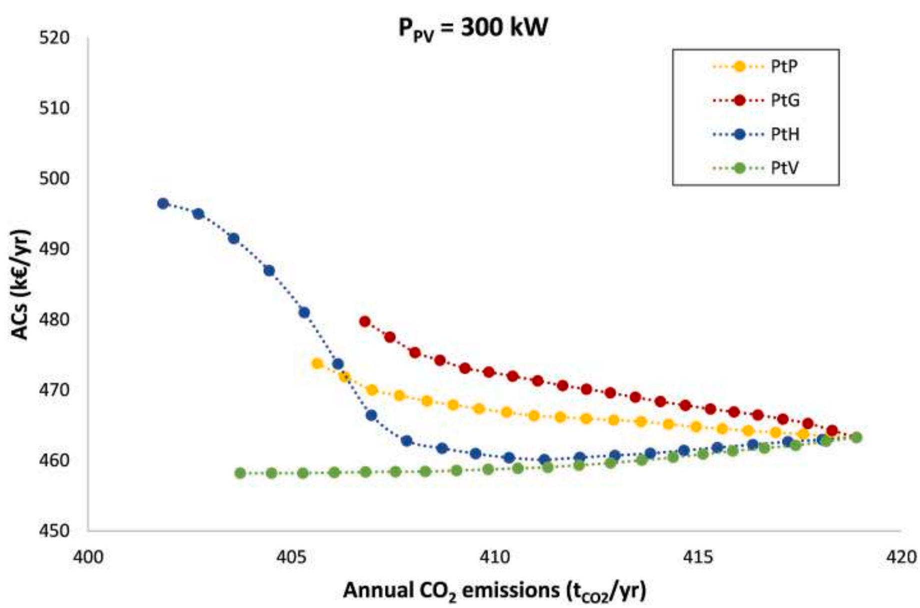

Fig. 14. Annual CO_2 emissions versus the ACs in the scenario with P_{PV} equal to 300 kW.

electricity in order to avoid several feed-in points on the power grid in a future where many decentralised renewable plants will be installed. In this view, electrolysis represents a local conversion of RES excess and, for the purpose of the present work, it can be considered as self-consumed electricity since it is not injected into the power grid.

The rated power and the average efficiency of the thermal plants in both conventional and smart scenarios are summarised in Table 7. Furthermore, efficiencies of PtX components and the annual PV plant capability have been reported in Table 8. Finally, the rated vehicle consumptions have been assumed in accordance with Ref. [89] and summarised in Table 9.

4. Results and discussion

A preliminary analysis between conventional and smart scenarios has been carried out to investigate the ability of the two systems to integrate the renewable generation. No PtX strategies are involved in this preliminary analysis, since it represents the assessment of the PV implementation in energy systems characterised by low and high end-use electrification, respectively.

SCR, SSR, ACs, f_{PV} and annual CO_{2eq} emissions have been calculated by changing the installed PV peak power (P_{PV}) up to 1000 kW. In Fig. 7, SCR and SSR versus the P_{PV} have been shown. Furthermore, ACs and annual CO_{2eq} emissions have been plotted in Figs. 8 and 9, respectively. Finally, in Fig. 10, the f_{PV} has been depicted.

In the conventional scenario, when f_{PV} is 1, less than 40% of the energy produced by the PV system is self-consumed. This value is reached with only 500 kW of PPV.

For the same P_{PV}, the electrification included in the smart scenario allows for a substantial increase in both SCR and SSR. For instance, with a P_{PV} of 600 kW, the SCR is 0.35 and 0.62 for conventional and smart scenarios, respectively.

The energy end-uses electrification allows to significantly increase the REC's ability of integrating VRES.

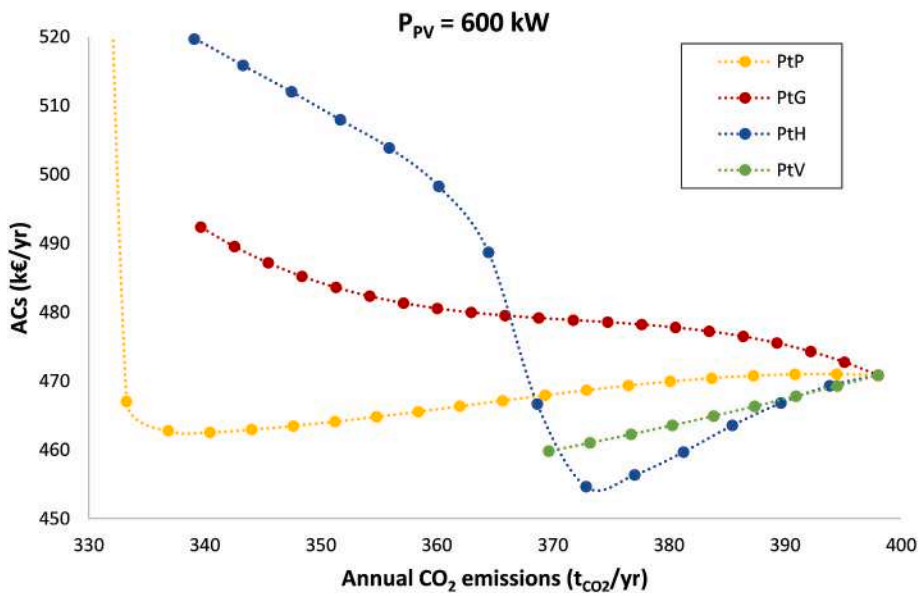

Fig. 15. Annual CO_2 emissions versus the SCR in the scenario with P_{PV} equal to 600 kW.

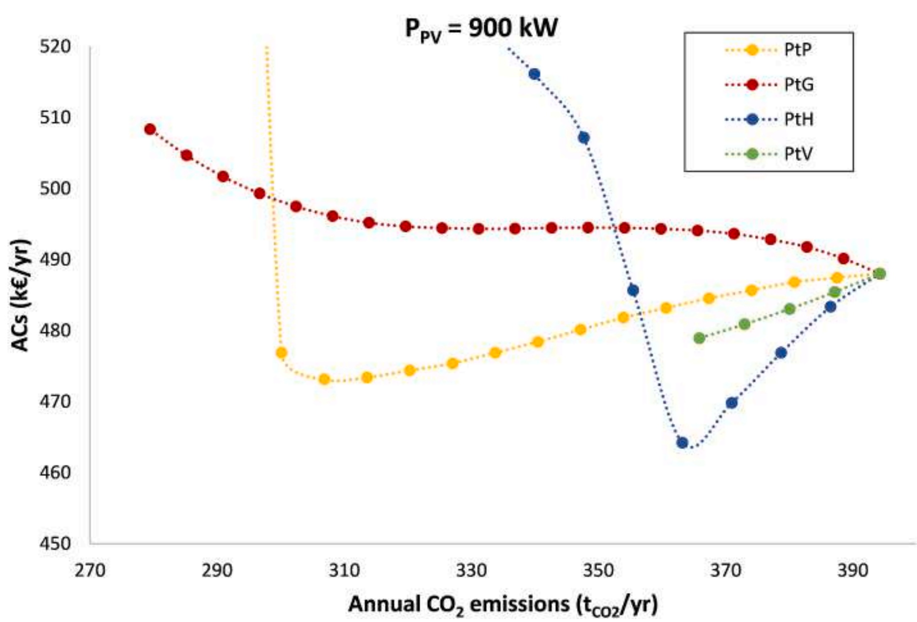

Fig. 16. Annual CO_2 emissions versus the SCR in the scenario with P_{PV} equal to 900 kW.

Nevertheless, in both the configurations, without any kind of energy storage system, the SCR rapidly decrease by raising the PV peak power. Besides, despite the significant increase in the P_{PV}, the SSR turns out to be extremely low.

The ACs and the annual CO_2 emissions related to the conventional energy systems are much higher than the smart one. In detail, annual emissions of the conventional energy system are twice as high as the smart one.

In the smart scenario, beyond the threshold value of P_{PV} equal to 300 kW, the larger the PV size, the smaller the ACs are. From the preliminary analysis, it can be concluded that integrating energy sectors along with electrifying energy end-uses is even more important than installing RES to reduce CO_2 emissions and minimise ACs. Only the smart energy system has been assessed for the further analysis, as it allows to implement all the PtX strategies.

Three PV configurations have been chosen in order to take into account different RES excess scenarios. P_{PV} values equal to 300 kW, 600 kW and 900 kW have been considered. The first one corresponds to the minimum cost configuration; the second one represents an intermediate value; finally, the third one is the scenario characterised by f_{PV} equal to 1. The main parameters associated to the selected scenarios have been summarised in Table 10.

4.1. Power-to-X strategies

In the three scenarios, the PtX strategies have been implemented and simulated by means of EnergyPLAN. By changing the energy storage systems size, SCR, ACs and CO_2 emissions have been computed. To compare the different systems, a correlation between SCR and annual costs has been elaborated.

In Figs. 11–13, SCR values versus ACs by implementing PtX strategies have been depicted for P_{PV} equal to 300 kW, 600 kW and 900 kW,

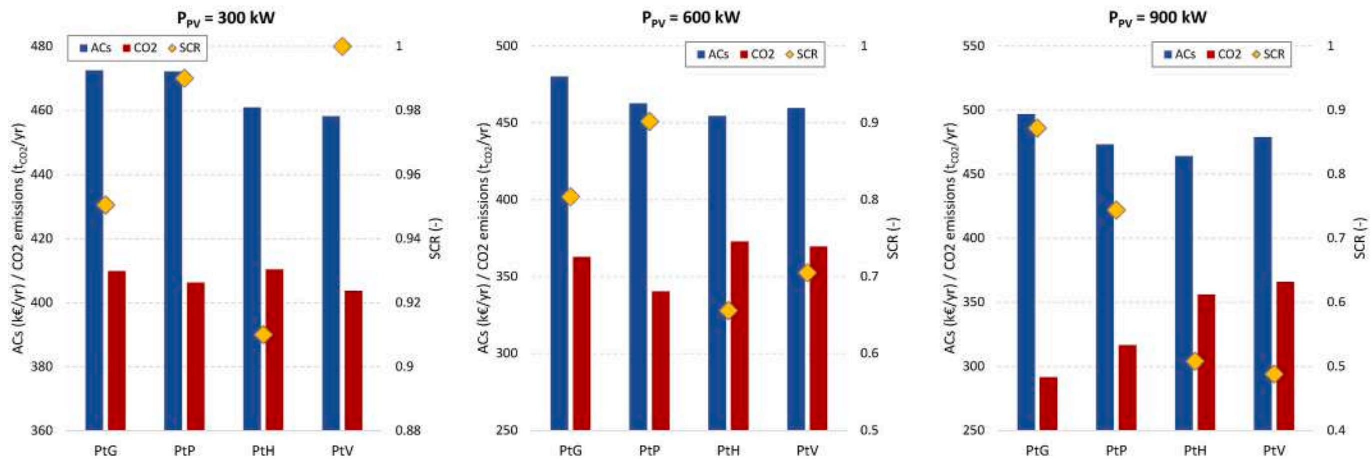

Fig. 17. SCR, annual costs and annual CO_2 emissions of Power-to-X configurations in different PV scenarios.

respectively. Furthermore, Figs. 14–16 present the correlations between annual CO_2 emissions and ACs for P_{PV} equal to 300 kW, 600 kW and 900 kW, respectively.

In order to more directly compare the different strategies, a comparative analysis of some Power-to-X configurations has been carried out. The sizing criteria has been defined as follows: minimum cost configuration for curves with a minimum, maximum implementation of the strategy for linearly decreasing curves and maximum implementation of the strategy for linearly increasing curves, without exceeding an annual cost increase of +2%.

In Fig. 17, SCR, annual costs and annual CO2 emissions of Power-to-X configurations in different PV scenarios have been depicted.

For low-RES excess, PtH and PtV strategies turn out to be the best solutions for improving the energy SC. This is due to the TES low costs and smart EV charging infrastructure. Nonetheless, both the systems present some intrinsic limitations when the RES excess increases. Indeed, enhancing the P_{PV}, those strategies are not able to achieve a SCR of 1. The PtV curve is linearly decreasing, however its potential is limited by the EV penetration in the community. Besides, the PtH system presents some constrains linked to the HP capacity and TES volume. Indeed, once a threshold value has been overcome, the increase in the storage size needed to improve the SCR make the solution no more cost-effective. The choice of the case study, characterised by a limited heating period, is penalising for the PtH strategy. Nevertheless, in all the simulated configurations, PtH strategy represents the first solution to be implemented for increasing the energy SC.

PtP system turns out to be a suitable solution for different RES excess conditions. Furthermore, in the configurations characterised by P_{PV} equal to 600 kW and 900 kW, electric batteries show a greater potential than PtH and PtV systems to increase energy SC. However, also the PtP curve has a threshold value beyond which an increase in the storage system size entails a significant reduction in the system cost-effectiveness. Furthermore, it is noteworthy that in each PV configuration the minimum cost is never achieved by the PtP system. The PtP application turns out to be able to reduce ACs only in the high-RES excess configurations. When the storage system sizes are small, the PtP system is not cost-effective, due to the high CAPEX of electric batteries.

PtG strategy is never the best solution, if not to increase the SCR in high-RES excess conditions. This is mainly due to the low remuneration considered for the hydrogen injection into the gas network. Notwithstanding, this strategy does not present the storage limits of other technologies as it exploits the local gas grid as a free storage infrastructure. Additionally, the PtG curve has a trend almost constant regardless of the PV rated power. That feature suggests that a reduction in the prohibitive costs of small electrolysers or a higher remuneration may make that strategy an attractive solution for the large VRES integration.

From the comparative analysis, it is noticeable that PtH and PtV strategies are the most cost-effective solutions. Those strategies allow the integration of non-dispatchable renewable generation at a lower cost than lithium-ion batteries. However, their potential is limited and, with large PV sizes, the level of SCR is very low.

The increase in PV size and the resulting increase in critical excess electricity production reduces the ability of PtX strategies to cost-effectively integrate renewable generation. Very high SCR values are only achievable by increasing the community annual costs in the configuration characterised by P_{PV} equal to 900 kW.

To sum up, the energy storage system implementation represents a cost-effective solution for reducing the electricity injection into the local power grid. Moreover, by improving the PV size along with PtH and PtV systems, ACs can be significantly reduced.

The analysis results concerning CO_2 emissions are closely related to those ones dealing with the SCR improving. That makes it possible to generalise the assessments made also for the discussion of the potential role of PtX systems in reducing CO_2 emissions. Hence, it can be stated that the cross-sectoral integration, between electricity, the heating and transport sectors, is a better solution than those that focus only on the electricity sector.

4.2. Sensitivity analysis

To generalise the discussion about strengths and weaknesses of PtX strategies, some boundary REC conditions have been varied. In such a way, the system applications in different REC models have been assessed.

The community PTHR, defined as the ratio between the annual electricity demand and the annual heating demand, in the reference scenario is equal to 0.23. Two other configurations, characterised by PTHR equal to 0.1 and 0.4, have been considered. In addition, the EV penetration has been analysed for values equal to 25%, 50% and 100%. In so doing, 27 scenarios for PtX strategies' implementation have been investigated.

In Figs. 18–20, the ACs versus the SCR by changing PTHR and P_{PV} have been depicted for the configurations characterised by EV penetration equal to 25%, 50% and 100%, respectively.

By increasing the PTHR, the competitiveness of PtH systems compared to PtV ones is reduced. The EV share increase positively affects the PtV strategy, however, even in the scenarios characterised by the full electrification of transport demand, that solution cannot achieve on its own the complete energy SC. In the scenarios with both low PTHR and low EV share, PtG system turns out to be an interesting solution for

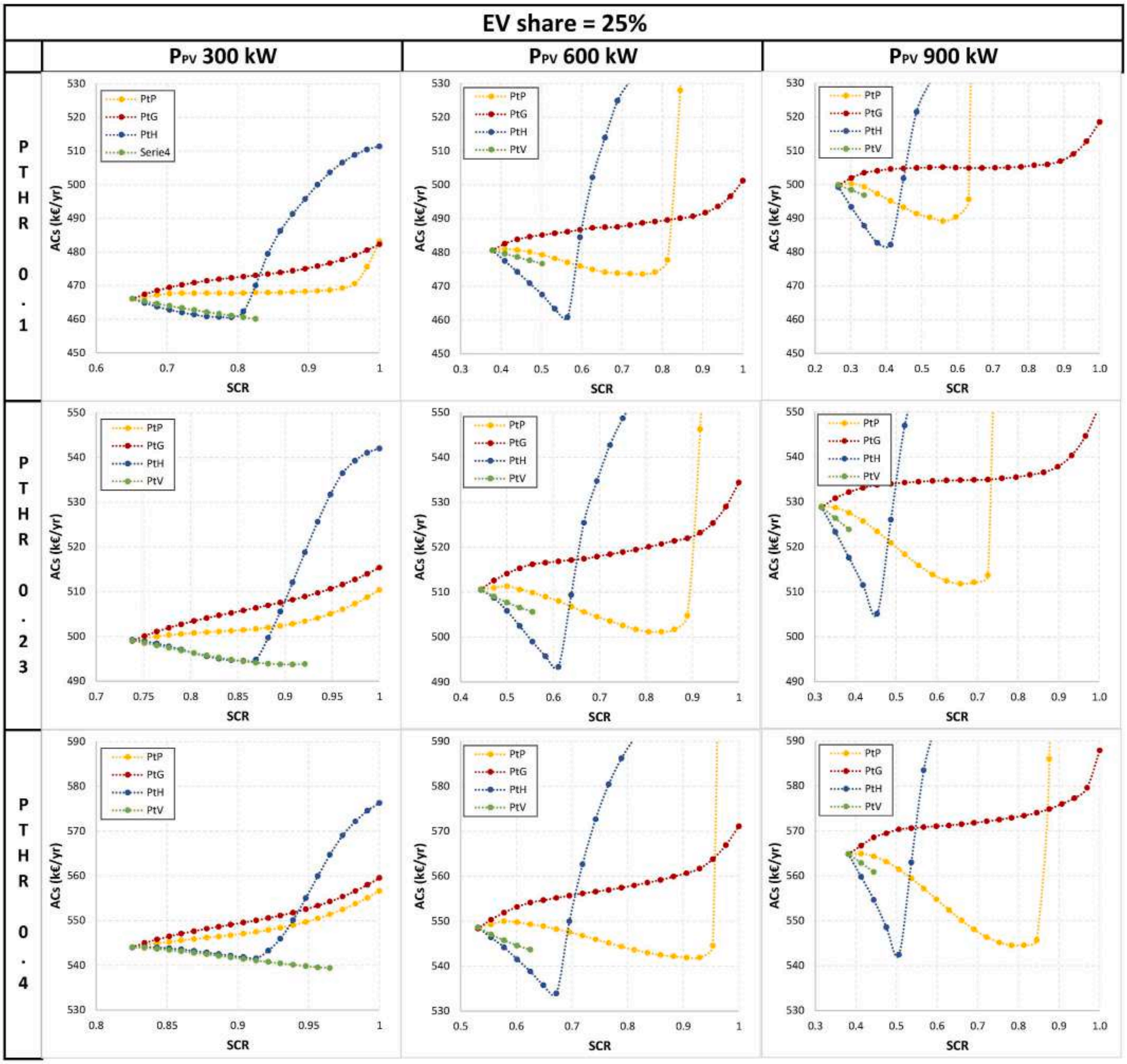

Fig. 18. ACs versus the SCR by changing PTHR and P_{PV} with EV penetration equal to 25%.

increasing the SCR. This is due to the low electrification level that reduces the REC ability to integrate VRES and likewise it reduces the potential of other PtX strategies. The EV penetration increase improves the competitiveness of PtP systems, especially to achieve high SC levels. Nevertheless, exploiting EV batteries is always more cost-effective than installing stationary batteries.

In almost all the REC configurations, the minimum cost solution is represented by the installation of 600 kW of P_{PV} along with the PtH system implementation. It should be point out that the best configuration can only be identified by integrating different PtX strategies. Nonetheless, optimising the REC configuration goes beyond the purpose of the present work, which is to discuss strengths and weaknesses of PtX applications.

4.3. Limitations of the work and further developments

The analysis in this paper aims to investigate the ability of different sector coupling strategies in maximising energy self-consumption. However, certain assumptions made in this paper and the choice of case study may influence the analysis.

In the present work only the integration of PV systems has been assessed and the REC is located in Rome. Thereby, the heat demand over the period in which higher RES excess occurs is only related to DHW. It can be supposed that this analysis is penalising for the PtH strategy. Indeed, by assessing the same system in better conditions, e.g. integrating Wind generation or evaluating REC in norther regions, better performances can be attained.

Potential further developments of this work are the integration of different renewable generation technologies and the analysis of sector coupling strategies under different weather conditions.

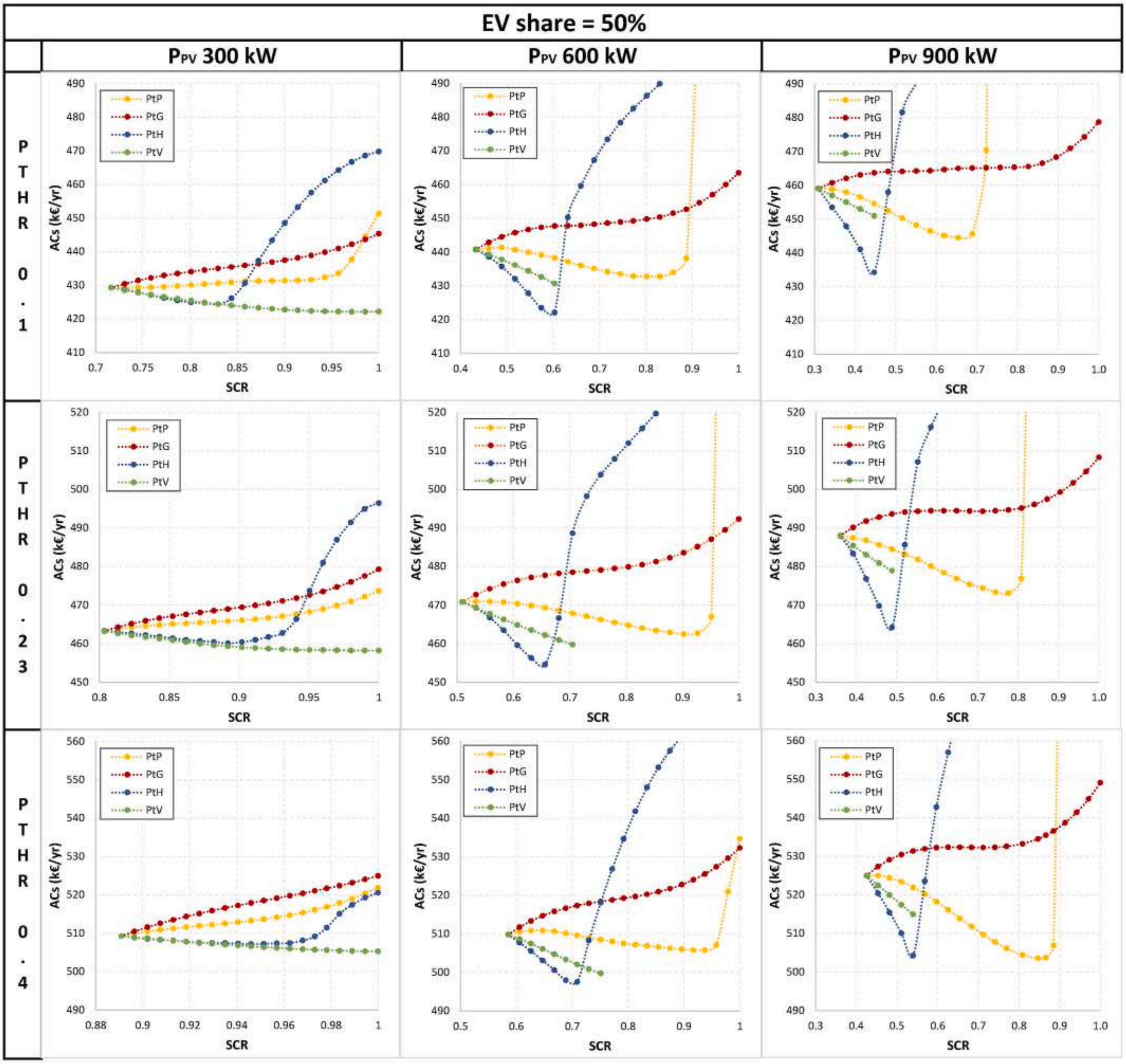

Fig. 19. ACs versus the SCR by changing PTHR and P_{PV} with EV penetration equal to 50%.

Furthermore, the EnergyPLAN software has been developed as a tool for national energy planning, although its application on a small scale already exists in the literature.

The software is suitable for these analysis on sector-coupling strategies, however, the simplified treatment of the technologies does not allow for the efficiency variation to be taken into account when varying weather conditions and load shedding. This simplification may affect the numerical results, however the variation from real data is small and the findings of this paper are not distorted.

Finally, the aim of this work is to discuss the strengths and weaknesses of PtX strategies, so their combined application has not been investigated. However, such an aspect can be the subject of further developments of the present work, either by combining the different technologies or by optimising the REC configuration.

5. Conclusions

The aim of this paper is to assess and discuss strengths and weaknesses of small-scale PtX applications in residential RECs. Power-to-Power, Power-to-Gas, Power-to-Heat and Power-to-Vehicle systems have been applied to a case study, consisting of ten buildings and two hundred flats. A preliminary analysis comparing a conventional and a smart energy system has been carried out. Three PV configurations have been considered to analyse the PtX strategies implementation in the smart energy system under different RES excess conditions. Furthermore, to broaden the analysis, some boundary conditions have been varied and 27 REC configurations have been studied.

The results of this work show how Power-to-X strategies represent a feasible and cost-effective solution to increase energy self-consumption in RECs. In detail, ACs and annual CO_2 emissions are highly reduced by moving from a conventional system towards a smart and integrated one.

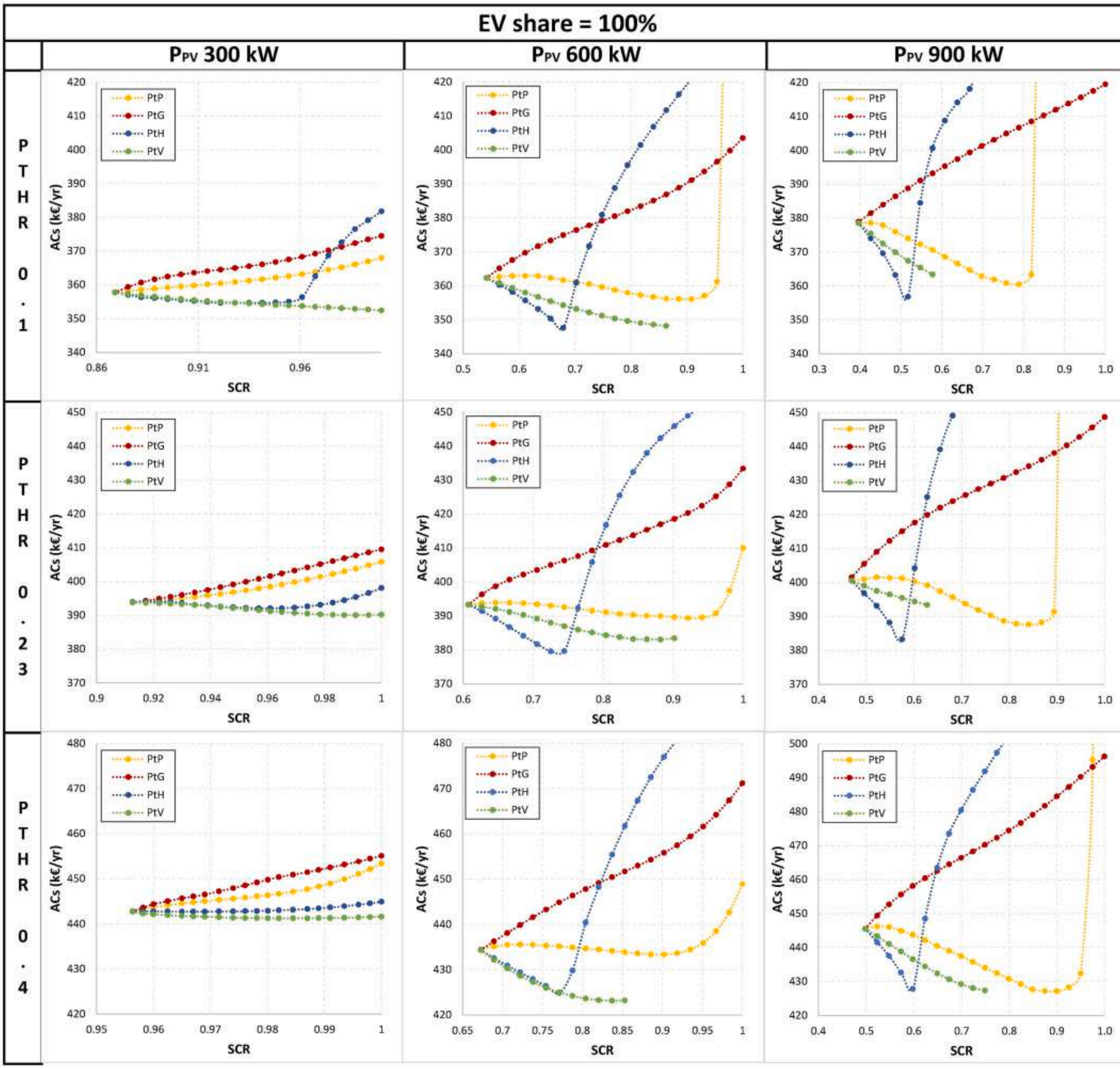

Fig. 20. ACs versus the SCR by changing PTHR and P_{PV} with EV penetration equal to 100%.

However, in both the configurations, without any kind of energy storage system, the SCR rapidly decreases by raising the PV peak power.

Integrating energy sectors and electrifying energy end-uses even takes priority over the RES installation for reducing CO2 emissions and minimising REC's ACs.

For low-RES excess, PtH and PtV strategies turn out to be the most interesting solutions for improving the energy SC. Nonetheless, both the systems present some intrinsic limitations when the RES excess increases.

The PtV curve is almost linearly decreasing, however its potential is limited by the EV penetration and owner participation. Even in the scenarios characterised by the full electrification of the transport demand, the complete energy SC cannot be achieved. However, exploiting EV batteries is always more cost-effective than installing stationary batteries. Besides, additional costs for national incentive schemes or energy trading fees could be needed for aggregate the EV owners and encourage the citizens' participation.

The PtH system represents the most cost-effective strategy for increasing the energy SC in almost all the simulated configurations. When the RES excess is high, there is a threshold value beyond which, as the storage size increases, the ACs rapidly increases. Thus, by increasing the PTHR, the PtH systems competitiveness compared to the PtV ones is reduced.

The PtP system turns out to be a viable solution in different RES excess conditions. Nonetheless, small-scale applications cannot reduce ACs because of high CAPEX of small size electric batteries. In configurations characterised by high-RES shares, they show a greater potential than PtH and PtV systems for increasing the SCR. The PtP curve also has a threshold value beyond which the system is no longer cost-effective. Moreover, it is noteworthy that in each REC configuration, the minimum cost is never attained by the PtP implementation.

The PtG strategy can never be considered the best solution, if not to substantially increase the SCR under high-RES excess conditions. This result is mainly due to the low remuneration which has been accounted for the hydrogen injection into the gas grid. Nevertheless, this strategy does not present the storage limits of other technologies as it exploits local gas pipelines as a free storage system. A likely forthcoming reduction in the high cost of small electrolysers or a higher hydrogen remuneration may make that strategy an attractive solution for the large VRES integration.

Finally, energy storage systems are crucial to reduce the electricity injection into the local power grid. Moreover, by improving the PV size along with the application of PtH and PtV systems, the REC's ACs can be significantly reduced. In conclusion, it emerged that the cross-sector integration is a better solution than focusing only on the electricity sector for improving energy, economic and environmental performance of renewable energy communities.

CRediT authorship contribution statement

Lorenzo Mario Pastore: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Gianluigi Lo Basso:** Supervision, Writing – review & editing. **Guido Ricciardi:** Formal analysis, Software. **Livio de Santoli:** 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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Nomenclature

ACs	Annual Costs (€/yr)
CAPEX	Initial Capital Expenditure (€)
COP	coefficient of performance (−)
CO_{2eq}	annual CO2 equivalent emissions (t_{CO2}/yr)
C	Costs (€/yr)
crf	Capital recovery factor (%)
i	Interest rate (%)
EP	Energy Performance Indicator (kWh/m^2yr)
$\eta_{th,el}$	Average efficiency of national thermal power plants (−)
f_c	correction factor (−)
f_e	emission factor (kg_{CO2}/MWh)
f_{nr}	non-renewable primary energy factor (−)
f_{PV}	PV factor (−)
P_{PV}	PV peak power (kW)
PE_C	REC's primary energy consumption (MWh/yr)
PFEC	Primary Fossil Energy Consumption (MWh/yr)
PTHR	Power-to-Heat Ratio (−)
RE_{SC}	renewable energy self-consumption (MWh/yr)
RE_{PV}	Annual PV production (MWh/yr)
SCR	Self-consumption Ratio (−)
SSR	Self-sufficiency Ratio (−)
τ	Lifetime (yr)
V	Storage volume (m^3)

Subscripts

c	Cooling
d	Demand
el grid	Electricity grid
ep	energy vector purchase
FUELS	Fossil fuels
h	Heating
imp	imported
nr	Non-renewable energy
O&M	operation and maintenance
PV	Photovoltaic
th	Thermal power plants

Abbreviations

4GDH	Fourth generation DH
ALK	Alkaline Electrolysers
DH	district heating
DHW	domestic hot water
EBs	Electric Batteries

EVs	electric vehicles
GHG	Greenhouse gas
HPs	Heat Pumps
NG	Natural Gas
PEM	proton exchange membrane
PtG	Power-to-Gas
PtH	Power-to-Heat
PtP	Power-to-Power
PtV	Power-to-Vehicle
PtX	Power-to-X
RECs	Renewable Energy Communities
RED II	Renewable Energy Directive
RES	Renewable energy sources
SC	Self-Consumption
SES	Smart energy systems
SOEC	solid oxide electrolysis cell
TES	thermal energy storage
V1G	Vehicle-1-Grid
V2G	vehicle-to-grid
VRES	Variable RES

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