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Opportunities for Power-to-Gas and Power-to-Liquid in CO_2-reduced energy scenarios: the Italian case

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ABSTRACT

Integration of renewable energy in the electricity market poses significant challenges on power grid management due to the volatility of these sources. In fact, the mismatch between renewable power generation and load curves, along with the need for grid stability, may lead to substantial curtailments when potential electricity supply exceeds demand. In this respect, the surplus from renewable energies can be conveniently exploited to produce hydrogen via electrolysis. This concept can be referred to as "Power-to-Gas" and "Power-to-Liquid" when synthetic grid gas and liquid fuels are respectively produced via syngas hydrogenation processes and is rapidly emerging as a promising measure in support of renewable energy penetration, leading to the decarbonisation of energy generation without affecting grid reliability. This study evaluates the impact of Power-to-Gas and Power-to-Liquid systems on future CO_2-reduced scenarios, characterized by increasing shares of renewable energies and electric vehicles under a holistic Smart Energy System perspective. Results show potential synergies among crucial energy sectors in terms of CO_2 emissions, curtailments and costs. Among the proposed options, synthetic grid gas produced by biomass gasification, and subsequent hydrogenation, leads to the best techno-economic scenario with a reduction of CO_2 emission of 30% with negligible change in yearly total costs.

KEYWORDS

Large-scale RES, Power-to-Gas, Power-to-Liquid, Electric Vehicles, CO_2 emissions reduction, Smart Energy System.

1 INTRODUCTION

Over the last decades, the design of an innovative technology framework in the energy sector has gained tremendous importance in energy policies for the achievement of a sustainable development, able to cater for the ever-increasing primary energy needs (presently made up of 81% by fossil fuels [1]) while reducing the level of greenhouse gases concentration in the atmosphere. Remarkable efforts, under the joint support of governments, research and industry, have been directed towards the reorganization of most carbon-intensive sectors as in electricity and heat generation, that together accounted for the largest share of global emissions (42%) in 2016, followed by transportation sector (24%) [2].

With this respect, global negotiations agree upon the key role of renewable energy sources (RES) in reducing CO_2 emissions by shifting consumption from fossil fuel to clean energy [3].

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Indeed, RES contribution to power supply has risen by more than 30% over the period 2010–2015 and, according to International Energy Agency projections, it is expected to expand by another 30% between 2015 and 2020; nonetheless, generation growth needs to accelerate further over 2020–2025, precisely by an additional 40% for renewables to meet the most aggressive CO_2 emissions reduction scenario [4].

However, the limited dispatchability and the natural intermittency of these sources create unbalances between generated electricity and demand, leading to a surplus when potential power generation exceeds the actual electrical load that has to be curtailed for grid stability and reliability purposes [5,6]. This calls for flexibility measures to help the power system cope with the uncertainty of supply coupled with the variability of demand [7,8], taking into account not only the technological framework but also legislative and financial interests driven by the institutions that ultimately establish policy strategy, development and investment in the energy sector. Therefore, large RES integration entails long-term policies and actions to improve the balance between electricity demand and supply so as to reduce the high volatility of electricity prices and restore opportunities for further investments [9–11].

Furthermore, at present, RES supply only slightly impacts non-electric needs such as heat and transportation that currently rely heavily on fossil fuels. With this respect, previous studies investigated the role of renewables in providing energy for the transport sector when consumption is shifted from fossil fuel to electricity by means of electric vehicles (EV) [12–14]. However, with reference to the Italian case, even assuming an entire replacement of conventional vehicles fleet and a tenfold increase in RES capacity as compared to 2015 level, CO_2 emissions can only be reduced by around 20% [14]. In fact, significant RES curtailments inevitably occur at high renewable installed capacities, calling for other solutions to exploit efficiently renewable potential.

Among the measures to tackle unbalances and capacity adequacy issues associated with RES fluctuating power, electricity storage systems are often regarded as a promising technology in the context of smart grids [15–19] along with flexible electricity demand [20,21] and transmission grid expansion [22]. State-of-art solutions are still not sufficiently effective or integrated, bring about significant costs [23–25] or have to deal with environmental impact [26] and scarce public acceptance [27].

As a result, other solutions should be investigated shifting attention from simple smart electricity grids towards a Smart Energy System that fosters potential synergy between different conversion technologies and allows RES deployment in different energy sectors through a holistic approach towards feasible 100% renewable-electricity systems [28–30].

In this regard, a particularly relevant research field involves converting the otherwise-curtailed surplus from renewable electricity to hydrogen, providing negative balancing power for hydrogen and oxygen production via electrolysis. This technology represents an option not only to mitigate RES unpredictability, buffering power curtailments, but also to diversify the mix of energy carriers with a simultaneous further decarbonization of the energy system [31–33].

Electrolysis is a well-known process able to dissociate water molecules by means of direct current, thereby producing pure hydrogen and oxygen [34]. This technology allows renewable energy surplus to be used to generate hydrogen, which can be stored or fed to chemical processes for the synthesis of liquid fuels. There are different electrolysis technologies currently applied worldwide, such as alkaline water electrolysis (AEL), polymer electrolysis membrane (PEMEL) and high-temperature electrolysis (HTEL), with different maturity levels [35]. AEL is a well-established and commercially mature technology also at large scale, PEM electrolysers are a proven technology currently commercially available at small scale, finally HTEL, despite its great potential, is still at laboratory scale [36,37]. The typical conversion efficiency, i.e. the ratio between the lower heating value of the hydrogen produced and the electrical input, is 50–70% approximately, with higher values for higher electrolysis capacity [33,37–39].

Hydrogen resulting from electrolysis can be injected into the natural gas grid, either directly (up to a limited volume fraction) [25,40] or used in methanation processes to convert CO_2-containing gases into synthetic natural gas ("Power-to-Gas", P2G) [41–44] or deployed for electrofuels production in the transport sector ("Power-to-Liquid", P2L) [45–49]. By replacing conventional petrol, diesel or jet fuel with synthetic fuels, CO_2 emissions can be also reduced in the heavy transport sector where EV still cannot penetrate, at least in the near future [49–52]. Moreover, electrofuels can be directly integrated into existing infrastructure, without particular technical or economic constraints [53].

At present, the technology itself of P2G/P2L systems is discussed in many papers, such as the ones referenced above, but very few analyse their impact in the wider context of continental [51] or national [54,55] smart energy systems characterised by high renewable penetration and a significant share of electric vehicles, while none considers the particular Italian case. Furthermore, these studies are not exclusively dedicated to the analysis of how P2G/P2L technologies impact the overall energy system, but these systems are implemented alongside several other different measures to pave the way to a 100% renewable energy scenario.

In view of this relative lack of analysis of the wider implications of P2G/P2L in the context of smart national energy systems, this study aims to investigate to what extent the surplus of RES power can be positively exploited for synthetic gaseous or liquid fuels production, under progressively increasing penetration of both RES in the electricity generation and EV in the transport sector. The influence of some relevant design and operating parameters in P2G/P2L pathways is also discussed.

The Italian energy system was taken as a case study, because Italy presents features that are shared by several other developed countries with high renewable potential and large fossil fuel consumption in the transportation sector, such as Denmark [54], Germany [55] or Spain [56]. In particular, Italy differs from Nordic countries in the availability of wind and solar energy, with this latter taking the lion's share among intermittent RES. Therefore, results for the Italian case can be particularly interesting as a reference for other national contexts where solar energy is the most abundant among renewables.

A variety of scenarios were modelled with the help of EnergyPLAN software according to the usage of hydrogen within the energy system. Different processes for syngas production were also assumed in which hydrogen combines with either biomass-derived syngas or biogas. Results were compared with respect to crucial indicators: CO_2 emissions, RES penetration curtailments and annual costs.

2 METHODOLOGY

This work further develops previous studies of the authors that modelled possible future scenarios characterised by progressively increasing shares of RES and EV in the energy system, providing also a detailed description with respect to the methodology used [57–59].

The analysis was carried out with help of EnergyPLAN computer tool, widely used in the literature for modelling complex energy systems on an hourly basis throughout the year using a holistic approach to exploit potential synergies among different energy sectors [60].

2.1 Base case scenario modelling

A reference scenario was defined for the Italian energy system at 2016, in line with the methodology used in previous works by the authors including additional improvements aiming to achieve a better overall characterisation of the current energy system. Tables 1–7 show data used to describe annual energy demand and supply, displaying values and relative sources. In particular, as regards electricity supply, the software requires CHP plants to be partitioned in two different groups depending on their size. Typically, large CHP plants, able to operate in an electricity-only mode, belong to Group 3, whereas Group 2 involves CHP plants working in back-pressure mode. In this study, large combined cycle and condensing plants were included in Group 3 (referred to as CHP3), while Group 2 (named CHP2) is assumed to be made up of back-pressure, internal combustion and gas turbine plants. District heating boilers belong to Group 1. All plants capable to work in electricity-only mode (conventional power plants and CHP3) were also grouped in what EnergyPLAN refers to as PP1 section in terms of overall capacity, efficiency (evaluated as a weighted average according to actual generation and fuel consumption) and fuel distribution (Table 5).

EnergyPLAN requires also several hourly distributions to perform simulations over the year: sources used are displayed in Table 8.

Base case scenario was validated against critical indicators with respect to 2016 data ensuring a variation within 2.2% (Table 9). Primary energy related to non-energy use and coal transformation were subtracted from the actual TPES, as not included in the EnergyPLAN model. CO_2 emission factors were derived according to the latest available national data [61].

Table 1. Electricity loads (TWh/year) at 2016

	Consumption	**Source**
Electric cooling	8.37	[62,63]
Electricity for heat pumps (individual)	18.63	[64]
Electric heating (individual)	8.37	[62]
Electricity for transport	11.72	[65]
Other electricity loads	285.86	[66]
Total demand (gross)	***332.95***	
Net import	43.18	[66]
Total domestic production (gross)	***289.77***	

Table 2. Fuel consumption (TWh/year) and efficiencies for individual heating at 2016

	Consumption (Sources: [67,68])	**Efficiency** (Source: [69])
Oil boiler	29.19	0.85
Natural gas boiler	262.73	0.90
Biomass boiler	79.44	0.75

Table 3. Transport sector fuel consumption (TWh/year) at 2016 (Sources: [65,68])

Fuel	**Consumption**
JP (Jet Fuel)	8.05
Diesel	262.92
of which biodiesel	*11.72*
Petrol	88.42
of which biopetrol	*0.38*
Natural gas	12.86
LPG	21.24
Electricity	11.16

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Table 4. Industry and various sector fuel consumption (TWh/year) at 2016 (Source: [68])

	Industry	**Various**
Coal	11.16	0.05
Oil	30.94	61.08
Natural gas	97.23	27.35
Biomass and waste	7.64	0

Table 5. Power plants capacity (MW) and efficiencies at 2016 (Source: [66])

Group	**Capacity**	η_{el}	η_{th}
PP1	58952	0.429	-
CHP2	5981	0.358	0.344
CHP3	20264	0.427	0.196

Table 6. Power plants fuel consumption (TWh/year) at 2016 (Sources: [66,68])

Fuel	**PP1**	**CHP2**	**CHP3**
Coal	100.58	1.96	7.63
Oil	36.54	13.64	30.73
Natural gas	219.60	44.76	134.98
Biomass	62.50	10.29	28.73

Table 7. RES capacity (MW) at 2016 (Source: [66])

	Capacity
Onshore wind	9410
Offshore wind	-
Photovoltaic	19283
River Hydro	5430
Dammed Hydro	18719
Geothermal	815

Table 8. Sources used for hourly distributions

Electricity demand	[70]	Cooling demand	[69]
Fixed Import/Export	[71]	Electricity for transport	[69]
District heating demand	[72]	Wind	[73]
Individual heating demand	[74],[75]	Photovoltaic	[73]
Industrial CHP heating demand	[69]	River Hydro	[73]
Industry gas demand	[74]	Geothermal	[73]

Table 9. Model validation with respect to 2016 actual data

	Model	***Actual***	***Difference***	***Source***
CO_2 emissions [Mt]	322.65	326.00	-1.0%	[76]
TPES [Mtoe]	140.20	143.40	-2.2%	[76]
RES electricity [TWh]	89.88	89.51	+0.4%	[66]
PP electricity [TWh]	94.58	93.57	-1.1%	[66]
CHP electricity [TWh]	104.95	105.13	-0.2%	[66]

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2.2 Future scenarios modelling

In previous papers [57,59] the authors proposed medium-long term scenarios for the Italian energy system with a progressively higher penetration of both EV in the transport sector and RES capacity in electricity generation. In these scenarios, the following parameters were considered unchanged with respect to 2016: transport demand (km/year, driving habits and number of total private vehicles), electricity (excluding demand for future EV and hydrogen generation via electrolysis), individual heating and cooling demand as well as installed power for conventional plants.

2.2.1 Modelling renewable penetration

In the simulated scenarios, intermittent RES installed capacity was parametrically increased from 2016 value (scenario labelled as RES2016, corresponding to a total of 28.7 GW) up to approximately nine times this level (259.3 GW), taking into account potential limits for wind technology, estimated at 17.15 GW [77]. More specifically, capacity was increased linearly for each of the intermittent RES technologies: in the case of wind energy, up to the aforementioned maximum potential, while in the case of solar energy up to the capacity required to reach a ninefold increase in overall intermittent RES capacity.

Among the possible scenarios thus defined, one particular case was identified to present results, that is loosely linked to RES generation targets as reported in the National Energy Strategy (SEN, *Strategia Energetica Nazionale*) [78]. SEN targets are given in terms of overall renewable generation, set to 55% of the overall national electricity supply at 2030 and 93% at 2050. Actually, these goals cannot be reached unless a profound reconfiguration of the whole energy system is implemented. Nonetheless, they were used to identify a single scenario, in which potential RES generation is 93% of total national electricity demand at 2016 (Table 1), using the same hourly distribution validated at 2016. The intermittent RES capacity that allows such potential generation is 213.2 GW (Table 10), which is 7.4 times the corresponding 2016 capacity. Therefore, results related to this particular scenario will be presented in the following sections with the label “7.4×RES”.

However, it is necessary to point out that the actual RES share of overall electricity generation can be significantly different from the 93% threshold for two reasons: on the one hand, electricity demand increases with respect to 2016 thanks to transport electrification and P2G/P2L electricity demand; on the other hand, significant overproduction and consequent curtailments may arise.

As a consequence, results for RES penetration for this particular scenario are unavoidably different from SEN targets, as discussed in section 3.1.

Table 10. Intermittent RES installed capacity (MW) at current and target energy scenarios

Scenario	**2016**	**7.4×RES**
Onshore wind	9410	14522
Offshore wind	-	920
Photovoltaic	19283	197753
Tot. intermittent RES	28693	213195

2.2.2 Modelling electric vehicles penetration

The impact of private transport only within the whole transportation sector has been assessed; conventional and electric vehicles were divided into different categories according to their market segment (as in small, medium and large) and to their sales over the last ten years [79]. A parametric analysis was undertaken with respect to EV penetration in the private

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transport sector, with the assumption of a linear decrease for petrol and diesel cars in each category and a simultaneous progressive replacement by EV (in the equivalent segment category). Conventional and EV technical specifications were derived as a weighted average of the actual circulating fleet composition.

To provide more reliable consumption data for EV, additional electricity consumption for auxiliary systems and real driving conditions were taken into account [80–82]. Fuel ~~economy~~ consumption for conventional vehicles, derived from manufacturers' declared data, were adjusted in each category to meet the more realistic overall higher value reported in Unione Petrolifera technical report [83]. Fuel consumption was also included for hybrid plug-in electric vehicles (PHEV) when exceeding the full-electric range [82]. PHEV were assumed to represent 30% of the EV medium and large size vehicle segment. The annual driving distance was set to 7280 and 13650 km/year respectively for petrol and diesel cars [83] with EV covering an average of 10367 km/year. Final electricity consumption for EV and PHEV was calculated taking into account a 90% charging efficiency. An example, referring to a 50% replacement of the conventional fleet, is shown in Tables 11–12.

For each EV penetration scenarios, two different options were analysed according to the implemented battery charging strategy and interaction with the grid:

- Smart charge: EV charge during low-power demand in order to meet drivers' needs to recharge the vehicle at a certain time as well as to avoid grid overloading;
- Smart charge and V2G: EV charge under a smart strategy and are able to feed electricity back to the grid when required.

The graphs displayed in the Results section refer to smart charge option, while results including V2G are discussed in Section 3.3.

Table 11. Conventional vehicles fuel consumption at 50% replacement

	Size	**Share**	**Initial vehicles ($\times10^6$)**	**Remaining vehicles ($\times10^6$)**	**Consumption (l/100 km)**	**Consumption (TWh/year)**
Petrol	Small	0.86	13.75	6.87	6.19	27.90
	Medium	0.13	2.04	1.02	6.79	4.54
	Large	0.01	0.12	0.06	9.38	0.37
	Total		**15.91**	**7.95**		**32.81**
Diesel	Small	0.35	5.27	2.63	4.79	16.87
	Medium	0.61	9.06	4.53	5.56	33.71
	Large	0.04	0.64	0.32	8.09	3.44
	Total		**14.96**	**7.48**		**54.02**

Table 12. EV electricity and fuel consumption at 50% replacement

Size	**Share**	**Consumption (kWh/100km)**	**Vehicles ($\times10^6$)**	**Electricity consumption (TWh/year)**	**Battery storage (GWh)**	**PHEV fuel consumption (TWh/year)**
Small	0.62	16.59	9.51	18.17	161.85	-
Medium	0.36	17.80	5.55	11.38	167.98	0.13
Large	0.02	22.37	0.38	0.97	22.62	0.12
Total			**15.43**	**30.52**	**352.46**	**0.25**

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2.2.3 Modelling Power-to-Gas and Power-to-Liquid options

Even with a complete replacement of EV in the private transport sector, charged using a smart charge option, consumption of fossil fuel is still significant in the heavy transport sector (where EV cannot penetrate) as reported in Table 13, and related emissions still represent 17% of the total. Moreover, previous analyses have shown that, despite a tenfold increase in RES capacity above 2015 level, curtailments were still as high as 31% of total electricity production [14].

Table 13. Fossil fuel consumption (TWh/year) in heavy transport at 2016 (Source: [65,83])

Fuel	**Consumption**
JP (Jet Fuel)	8.1
Petrol	22.6
Diesel	154.5

With this respect, this study investigates solutions to productively exploit the remaining, and still significant, excess of RES electricity production aiming to a further CO_2 emissions reduction within the energy system. Such excess could be used to produce hydrogen and thence synthetic natural gas or liquid fuels according to a Power-to-Gas or Power-to-Liquid approach respectively. In this context, particular focus was given to the production of electrofuels to ultimately replace fossil fuels in heavy transportation, obtained via chemical synthesis, by means of the biogas/syngas hydrogenation process. Two main alternatives for syngas production were assumed, according to the options available in EnergyPLAN:

- Methanation of biogas (scenarios labelled as “biogas”);
- Hydrogenation of syngas from biomass gasification (scenarios labelled as “biomass”).

In both cases, two different destinations for the resulting syngas are herein evaluated:

- Power-to-Methane: production of Synthetic Natural Gas (SNG) to be injected in the grid gas (scenarios labelled as “SNG”);
- Power-to-Liquid: syngas from biomass gasification is used for fuels production, such as methanol, dimethyl ether (DME) and Jet Fuel, replacing fossil fuels in heavy transport sector (scenarios labelled as “P2L”); liquid fuel production is assumed to gradually increase with EV penetration until it completely replaces fossil fuel in heavy transport.

Three different combinations can be obtained from the above-mentioned options with respect to the gas to be hydrogenated and the destination of the final product, as described in the following.

2.2.3.1 Biogas→SNG

In this case, CO_2 is removed from biogas and reacts with hydrogen according to the Sabatier reaction:

$$\mathrm{CO_2} + 4\ \mathrm{H_2} \rightarrow \mathrm{CH_4} + 2\ \mathrm{H_2O} \tag{1}$$

The overall process can be described as follows:

a) Hydrogen production by water electrolysis;
b) Reactant compression;
c) Methanation reaction to convert CO_2 and H_2 into methane;
d) Gas purification to fulfil requirements for natural gas injection into the grid; only SNG scenarios are considered for biogas consumption.

Overall, such conversion can be highly efficient as a series of reactors, equipped with heat exchangers, could be used to cool down the gas stream (being the reaction highly exothermic). On the other hand, significant additional energy supply is needed to increase reactants pressure and for upstream and downstream gas purification processes [43].

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2.2.3.2 *Biomass→SNG*

Instead of pure CO_2, in this case the hydrogenation process involves synthetic gas; the presence of CO has a generally positive effect on CO_2 hydrogenation reaction that in turn occurs following two different steps:

$$\mathrm{CO_2 + H_2 \rightarrow CO + H_2O} \tag{2}$$

$$\mathrm{CO + 3\,H_2 \rightarrow \ CH_4 \ + \ H_2O} \tag{3}$$

It is worth mentioning that the inlet gas stream has to feed an adequate amount of CO_2 so as not to favour the water-gas shift reaction (the first reaction from right to left, which generates CO_2 from CO).

2.2.3.3 *P2L*

In this scenario, methanol and DME are produced by means of the following reactions:

- CO_2 hydrogenation: $\mathrm{CO_2 + 3\,H_2 \ \rightarrow CH_3OH + H_2O}$
- CO hydrogenation: $\mathrm{CO + 2\,H_2 \rightarrow CH_3OH}$
- Water-gas shift: $\mathrm{CO + H_2O \rightarrow CO_2 + H_2}$
- Methanol dehydration: $\mathrm{2\,CH_3OH \rightarrow CH_3OCH_3 + H_2O}$

In order to shift the reaction towards DME the amount of CO_2 in the inlet gas stream has to be reduced. Process pressures are relatively high (40–50 bar) with temperatures around 250 °C. The overall efficiency results highly limited by the reaction thermodynamics.

2.2.3.4 *Overview of simulation parameters*

Operating parameters for biomass gasification plants are listed in Table 14. Default parameters from the latest version of EnergyPLAN were used [84], which are in line with literature data referring to the process of glucose gasification through anaerobic digestion and cellulose steam gasification [49,85]. Steam efficiency refers to the marginal efficiency of heat generation of a CHP plant (related to the additional fuel input to obtain the required amount of steam for the same electricity output): in EnergyPLAN gasification steam is obtained from biomass taking into account this pathway. Steam share is the fraction of steam to total biomass input (including biomass used for steam generation). Table 15 displays efficiency values and hydrogen shares for hydrogenation processes, derived from available literature data [33,85].

For simplicity, production of biogas and syngas from biomass gasification was assumed to have a constant hourly distribution, and as a consequence consumption of hydrogen is also constant in time. This assumption clearly does not allow utilizing to the maximum possible extent RES potential generation, as discussed in the Results section 3.2.

Electrolysers were implemented in the model with the following parameters: 73% efficiency (LHV based), taking into account solid oxide electrolyser cells (SOEC) operation and hydrogen compression up to 80 bar [33,37,38] (it is worth mentioning that this is a rather conservative choice, since higher efficiency values can be found in the literature as a forecast for future SOEC operation [86]); installed capacity equal to four times the average power required to guarantee the annual hydrogen production for syngas/biogas hydrogenation processes estimated on the amount of electrofuel needed; a six days' worth hydrogen storage capacity.

A parametric analysis was also performed with respect to electrolysers and storage capacity to assess their relative impact on the energy system.

In "P2L scenarios", the amount of liquid fuels produced was linearly increased from zero up to the complete replacement of fossil fuel consumption in the heavy-transport sector. The fraction of heavy-transport fuel covered by P2L was assumed equal to the fraction of EV in the private-transport sector (section 2.2.2). In "SNG" scenarios, the amount of syngas injected in the gas grid corresponds to the syngas required for electrofuel production in the equivalent "P2L" alternative.

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Figs. 1–3 show schematically the energy flows involved in P2G/P2L pathways (gasifier electricity consumption is not shown for simplicity since it amounts to just 1% of the total energy input).

Table 14. Gasification plant operating parameters

Parameter	**Value**
Steam share	0.13
Steam efficiency	1.25
Cold gas efficiency	0.90

Table 15. Hydrogenation methods operating parameters

Method	**Efficiency**		**Hydrogen share**	
	SNG	**P2L**	**SNG**	**P2L**
Biogas hydrogenation	0.83	-	0.50	-
Syngas hydrogenation	0.87	0.60	0.36	0.38

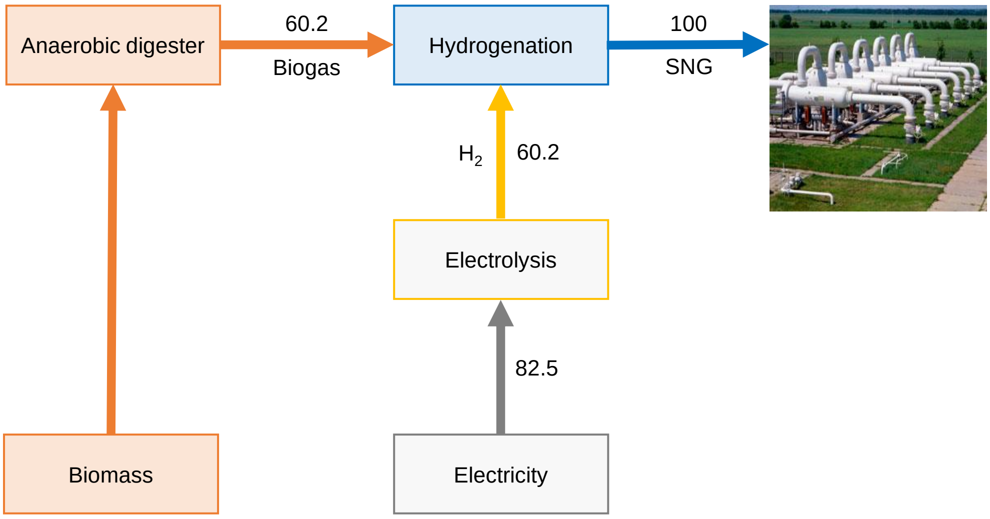

Figure 1. Schematic energy flows for the Biogas→SNG pathway

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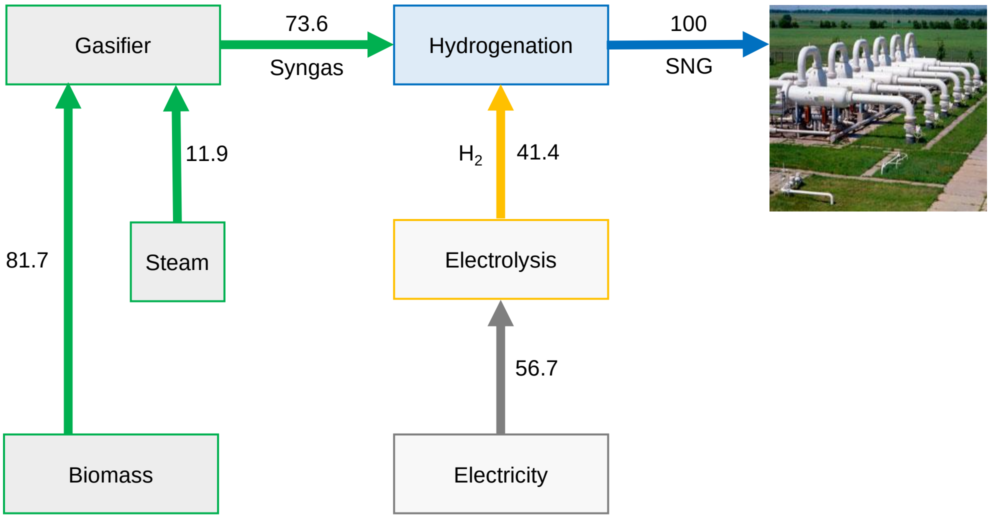

Figure 2. Schematic energy flows for the Biomass→SNG pathway

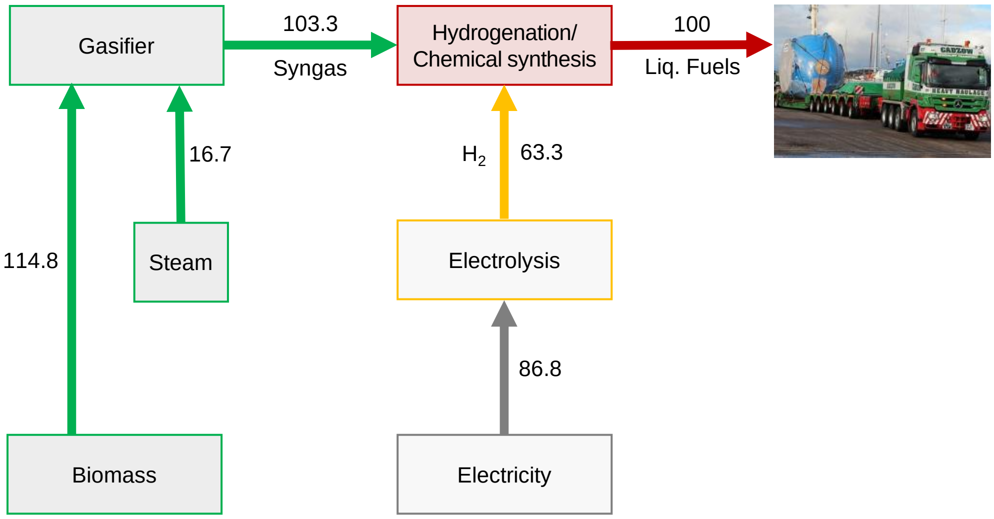

Figure 3. Schematic energy flows for the P2L pathway

2.2.4 *Cost structure*

A preliminary cost analysis has been undertaken to evaluate the impact of increasing RES capacity and EV penetration from an economic perspective. Cost data have been mainly derived from the EU-funded Heat Roadmap Europe project [87] for the Italian case and only those parameters relevant to the analysis have been herein recalled, precisely costs related to intermittent RES, fuel, hydrogen production, biogas and biomass gasification plants as well as costs related to methanation and synthesis processes. For this latter, in particular, production costs were obtained from a comprehensive review, including the costs and efficiencies for the separate production steps, as provided by Brynolf et al. [86]. Given the foreseen decrease in battery costs [88,89], and the medium-long term perspective of this analysis, EV average purchasing price is assumed to be the same as for conventional cars. Indeed, some economists argue that "the upfront cost of EV will become competitive on an unsubsidized basis starting in 2024" [90].

Economic data for the 7.4×RES scenario are based on forecasts to 2050. CO_2 price due to carbon tax has been set to 43.5 €/tCO_2 and interest rate to 3% [69].

Table 16. Intermittent RES related costs at 2050 (Source: [69])

	Investment [M€/MW$_e$]	**Period [Years]**	**O. & M. [% of Inv.]**
Onshore wind	0.86	30	3.41
Offshore wind	1.39	30	1.93
Photovoltaic	0.66	40	1.11

Table 17. Fuel price [€/GJ] (Source: [69])

Coal	2.4
Fuel Oil	9.7
Diesel Gasoil	12.1
Petrol/JP	12.1
Natural gas	9.3
LPG	13.4
Biomass	8.5

Table 18. Gas and electrofuel production-related costs (Source: [86], [69])

	Unit	**Price [M€/unit]**	**Period [year]**	**O. & M. [% of Inv.]**
Electrolyser	MW$_e$	0.4	23	4.3
Hydrogen storage	GWh	5.9	20	2.1
Methanation	MW	0.2	25	4.0
Liquid fuel synthesis	MW	0.3	25	4.0
Gasification plant	MW	1.2	20	2.4
Biogas plant	TWh/year	147.4	20	14.0

3 RESULTS AND DISCUSSION

3.1 Impact of P2G/P2L options

Different scenarios have been compared with respect to critical indicators as in CO_2 emissions, RES penetration, energy curtailments, and annual costs. Table 19 lists results for both SNG and P2L options for the 7.4×RES scenario. As for CO_2 emissions, variations are evaluated with respect to the 2016 scenario.

Generation of SNG from biomass (Biomass→SNG scenario) leads to the highest values in terms of CO_2 emissions reduction (-29%) at significant RES penetration. In this scenario, the amount of SNG generated is 26.8% of total natural gas demand. Additional biomass demand amounts to 169 TWh (thus almost doubling 2016 biomass consumption [68]) for the 7.4×RES, 100%EV+biomass→SNG scenario, and research should be conducted to ensure that such value lies within the sustainable threshold. However, in a real case, both biogas and biomass pathways should be followed, thus mitigating the increase in either biogas or biomass consumption.

Syngas destination affects CO_2 emissions: when syngas replaces fossil fuel for transportation (P2L), instead of natural gas (SNG), slightly worse results are obtained due to the lower overall process efficiency, despite the higher emission factors of diesel and petrol as compared to natural gas. Same considerations apply to RES share and curtailments.

As displayed in Fig. 4, when EV replace entirely the fleet of conventional vehicles, CO_2 emissions decrease significantly with RES capacity until a threshold is reached. For RES capacity above this threshold, CO_2 emission reduction is much slower due to the exponential rise in curtailments (Fig. 5) [14], leading to a saturation in RES penetration (Fig. 6). However, P2G/P2L technologies shift this threshold to much higher values, and a 60% RES share of electricity generation is achievable with an increase in RES capacity by 7.4. For comparison, Varone and Ferrari found that in Germany an eightfold increase in RES capacity and the adoption of P2G/P2L (without any electrification of the transport sector) could result in a 79% RES share of electricity generation.

Table 19. CO_2 emissions variation, RES share and curtailments at different EV penetration for 7.4×RES scenario

ΔCO_2	**0%EV**	**20%EV**	**40%EV**	**60%EV**	**80%EV**	**100%EV**
Base	-9.79%	-12.48%	-15.20%	-17.90%	-20.50%	-23.06%
Biogas→SNG	-9.79%	-14.42%	-18.23%	-21.34%	-23.56%	-24.38%
P2L	-9.79%	-15.11%	-19.57%	-23.24%	-25.84%	-27.12%
Biomass→SNG	-9.79%	-14.60%	-18.88%	-22.73%	-26.16%	-28.92%
RES share (% of total electricity production)						
Base	55.32%	56.24%	57.17%	58.05%	58.71%	59.27%
Biogas→SNG	55.32%	58.94%	60.62%	60.97%	60.04%	57.50%
P2L	55.32%	59.01%	60.64%	60.85%	59.57%	56.86%
Biomass→SNG	55.32%	58.22%	59.87%	60.60%	60.62%	59.71%
Curtailments (% of total electricity production)						
Base	44.95%	40.76%	36.69%	32.81%	29.29%	26.04%
Biogas→SNG	44.95%	30.18%	19.25%	11.31%	5.94%	3.18%
P2L	44.95%	29.63%	18.47%	10.49%	5.37%	2.73%
Biomass→SNG	44.95%	33.19%	23.83%	16.52%	10.83%	6.83%

Smaller emissions reductions are achieved when hydrogen is used for biogas methanation (biogas→SNG), as a consequence of the lower system efficiency combined with the higher share of hydrogen used in the process (see Table 15). In fact, when a surplus of RES power is not available, or relatively small, or partially absorbed by the increased electricity demand from EV, conventional power plants are required to provide the additional electrical power for hydrogen production.

It is interesting to compare these results with national targets set by SEN [78]: according to these objectives, sectors included in the Emissions Trading Scheme (ETS) should reduce emissions by 57% with reference to 2005, while for non-ETS sectors the target is 33%, resulting in a 42.7% overall reduction (332 Mt vs. 579 Mt). In 2015, overall CO_2 emissions were 433 Mt, so that the expected decrease in the period 2015–2030 is 23.3%. Even though the energy sectors included in this analysis do not cover the overall emissions, this figure can be compared to the results of this analysis to gain a qualitative evaluation of how feasible it is to reach the proposed targets: Fig. 4 shows that a 23.3% reduction in the energy sectors can be achieved only with a deep electrification of private transport and very large RES installed capacity (above the targets for 2030). Power-to-Gas and Power-to-Liquid technologies actually become really helpful only for more substantial emission reduction targets.

Besides, these results can be compared to SEN targets for RES share of overall electricity generation: as mentioned in section 2.2.1, these targets are 55% for 2030 and 93% for 2050. Fig. 6 shows that the first target is within reach with the proposed actions, even though reaching it by 2030 is questionable: large increase in RES capacity (above 6 times the current value), deep electrification of private transport, adoption of P2G technologies to displace around 30%

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of natural gas consumption. Achieving the 2050 target, instead, requires a profound reconfiguration of the whole energy system, with an even larger increase in RES generation to be ultimately exploited in other sectors, such as residential heating, that are only marginally affected by those considered in this analysis.

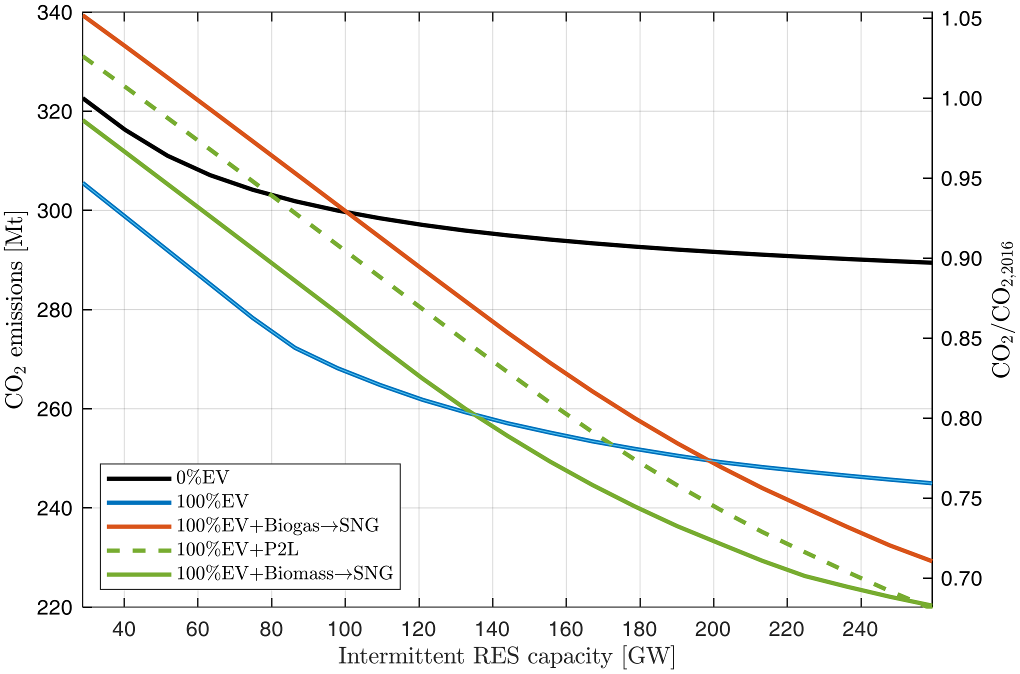

Figure 4. CO_2 emissions for increasing intermittent RES capacity and different P2G/P2L options

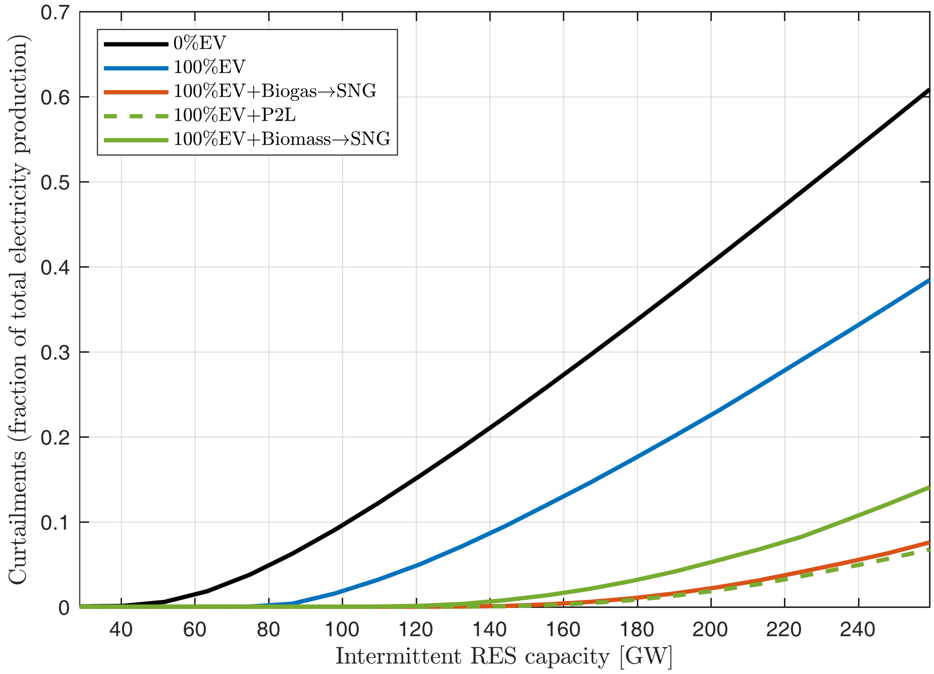

Figure 5. Curtailments for increasing intermittent RES capacity and different P2G/P2L options

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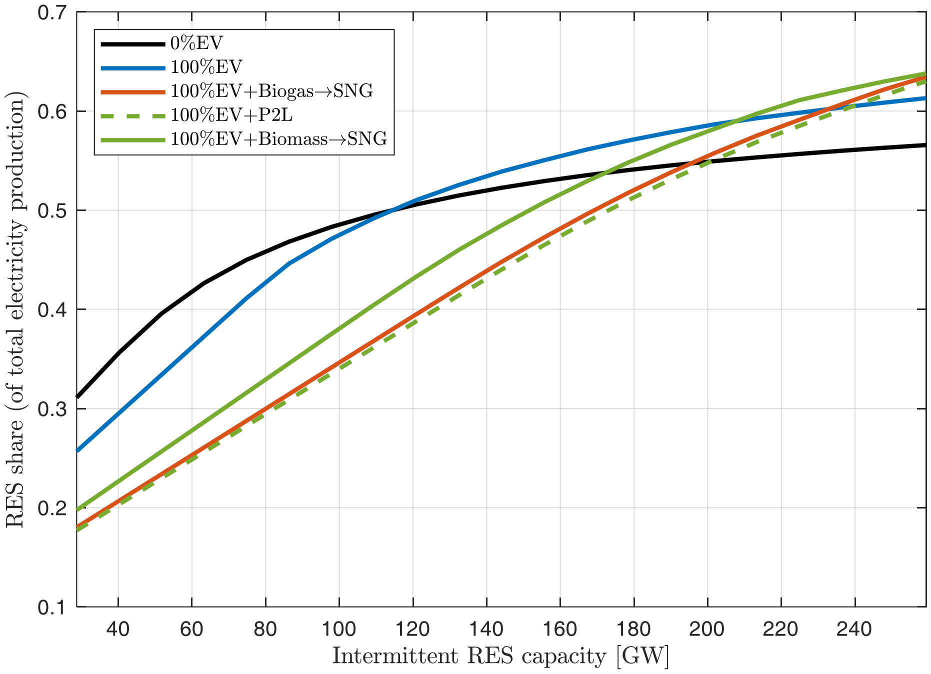

Figure 6. RES share for increasing intermittent RES capacity and different P2G/P2L options

Fig. 4 also underlines that the growth in electricity demand related to P2G/P2L processes becomes favourable only when the surplus of RES production increases over a certain threshold, ultimately leading to an overall reduction in CO_2 emissions. Nonetheless, besides a reduction of RES surplus, the non-simultaneity between intermittent RES potential generation and electricity demand calls for additional production from conventional power plants thus curbing the potential reduction of CO_2 emissions.

Figs. 7–8 compare electricity demand along with curtailments and electricity generation for 100%EV without any P2G/P2L and 100%EV+biogas→SNG scenario respectively, at 7.4×RES during approximately ten days of spring when a surplus of RES electric power is expected to be at its highest level. Both RES surplus reduction and fossil fuel power plants increase is evident in Fig. 8.

The additional conventional power plant generation can also be observed in Figs. 9–10, which show CO_2 emissions from different sectors for 7.4×RES, 100%EV scenario with no P2G/P2L option and 7.4×RES, 100%EV+biogas→SNG scenario respectively. Comparison of these charts also underlines that significant emissions are related to the heavy transport sector, and these can be mitigated with a P2L approach at the cost of a further increase in conventional power plant emission (Fig. 11), even though this solution does not compare favourably in terms of emission reduction with the biomass→SNG option (Fig. 12).

Similar results can be potentially achieved in those national energy contexts characterised by high renewable potential as well as large fossil fuel consumption in the transportation sector [54,56,59].

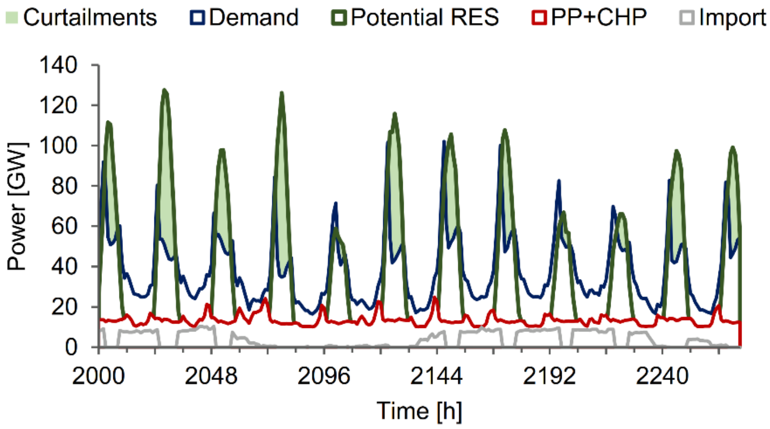

Figure 7. Power generation and demand for 7.4×RES, 100%EV scenario

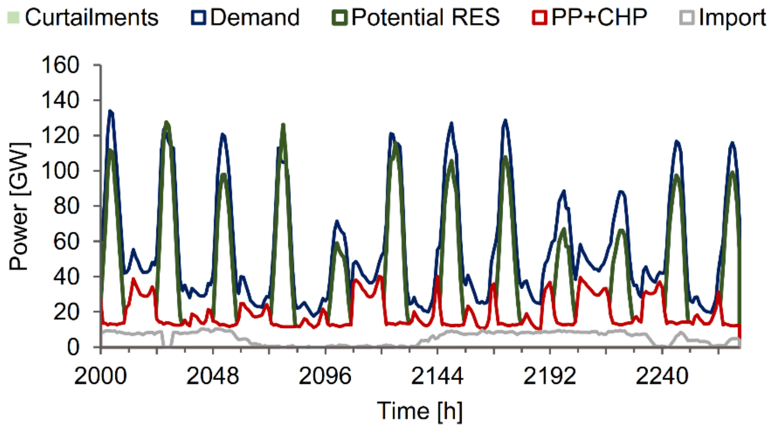

Figure 8. Power generation and demand for 7.4×RES, 100%EV+biogas→SNG scenario

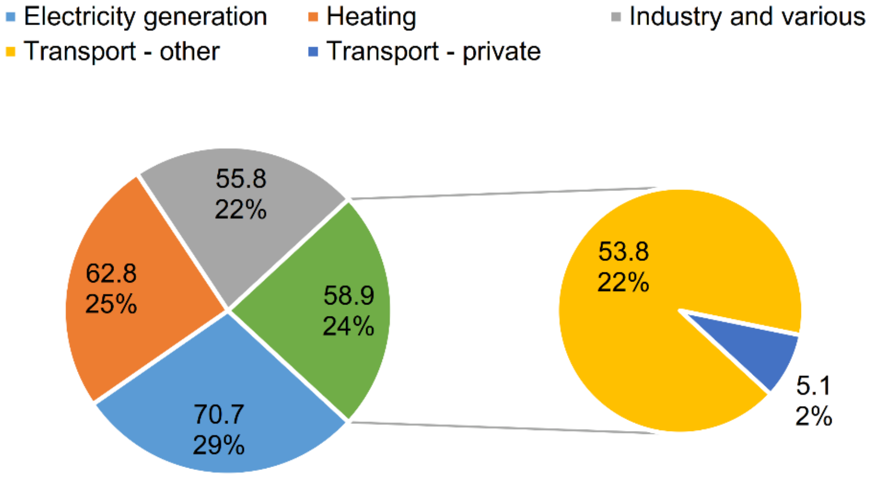

Figure 9. CO_2 emissions by sector for 7.4×RES, 100%EV scenario

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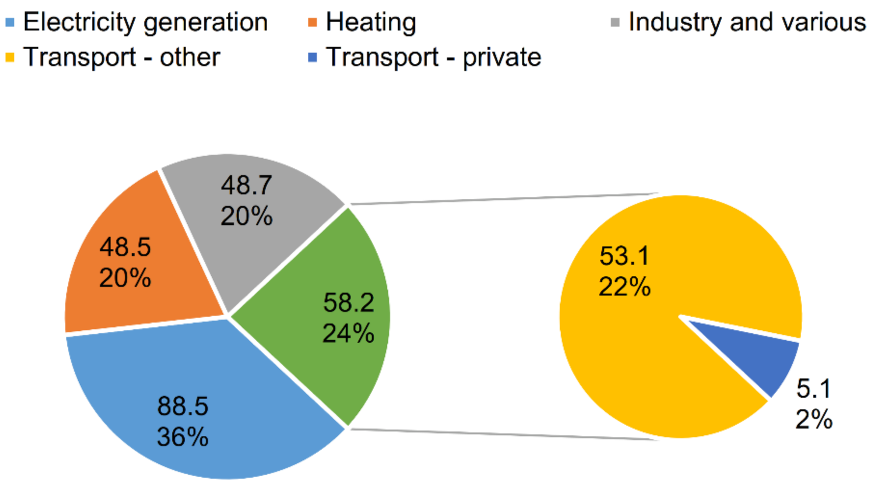

Figure 10. CO$_2$ emissions by sector for 7.4×RES, 100%EV+biogas→SNG scenario

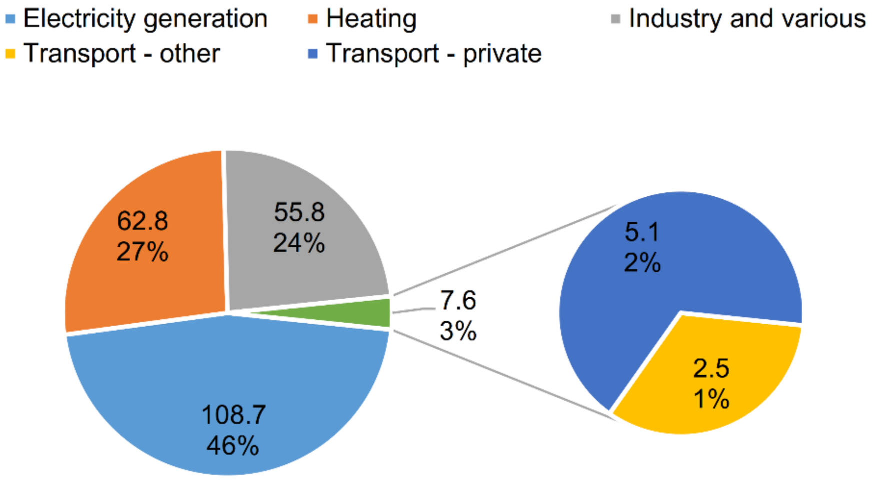

Figure 11. CO$_2$ emissions by sector for 7.4×RES, 100%EV+P2L

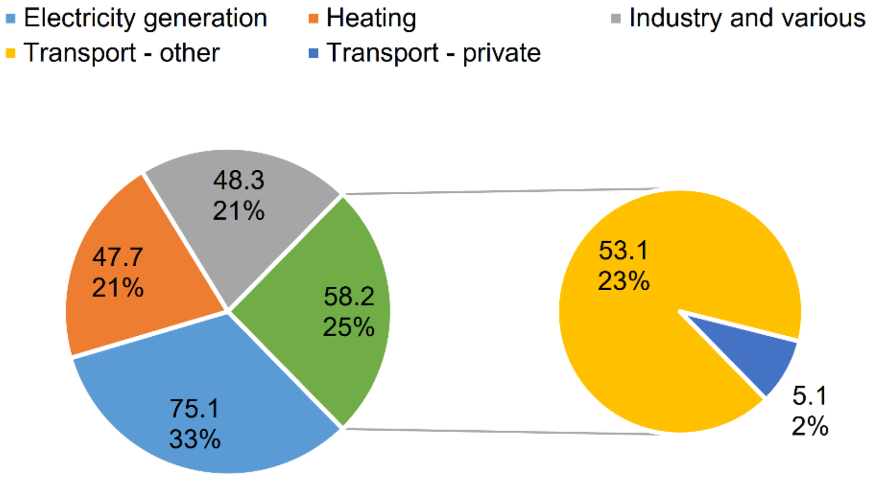

Figure 12. CO$_2$ emissions by sector for 7.4×RES, 100%EV+biomass→SNG scenario

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3.2 Sensitivity analysis

A sensitivity analysis was carried out in order to evaluate the impact of the most significant parameters used to describe Power-to-Gas and Power-to-Liquid pathways (section 2.2.3). In particular, CO_2 emissions and curtailments were assessed for different values of electrolyser installed capacity, hydrogen storage capacity, biogas/syngas hydrogenation efficiency (Figs. 13–16).

Electrolyser efficiency was not included in this analysis because of its limited influence on main technical results: indeed, if a prescribed amount of hydrogen needs to be produced to cover hydrogenation demand, a variation in electrolyser efficiency only results in a change in electrolyser capacity, with marginal effects on emission reduction and curtailments, but obviously with an economic impact related to the investment cost for electrolysers.

Figs. 13–14 show CO_2 emissions and curtailments for the 7.4×RES, biomass→SNG scenario against electrolyser capacity, which is measured with reference to the minimum possible capacity needed to satisfy annual hydrogen demand, corresponding to the average power required to guarantee hydrogen production for syngas/biogas hydrogenation processes, estimated on the amount of electrofuel needed. This minimum electrolyser capacity is 11.95 GW for an 87% hydrogenation efficiency. Results are parameterised against hydrogen storage capacity and hydrogenation efficiency.

As mentioned in section 2.2.3, demand for biogas and syngas for P2G/P2L was assumed constant throughout the year, and as a consequence hydrogen consumption for hydrogenation processes is constant too. This means that, if no storage capacity is available, hydrogen production must also be constant, with the result that an increase in electrolyser capacity reduces neither emissions (Fig. 13) nor curtailments (Fig. 14).

Obviously, better results could be obtained by allowing flexible biogas and syngas generation distributions, in order to make larger use of potential surplus RES generation. In the current version of EnergyPLAN software it is possible to implement an hourly annual distribution for biogas and syngas generation; however, this distribution cannot be managed flexibly and automatically during the simulation in order to optimize electricity consumption with reference to CO_2 emissions and curtailments, but it must be predetermined before simulating the scenario.

Hydrogen storage capacity introduces some flexibility, making it possible to decouple, to some extent, hydrogen consumption and production. This allows a more efficient use of potential RES generation, with the result of lower emissions and curtailments. In this case, an increase in electrolyser capacity provides more flexibility, with a significant positive impact on emissions and curtailments.

Counterintuitively, better hydrogenation efficiencies lead to larger curtailments. This is because the amount of SNG to be produced is constant, therefore this amount requires less electricity consumption: since electricity for hydrogen generation is supplied by both conventional and renewable power plants, a decrease in electricity consumption for this purpose reduces emissions from conventional power plants (Fig. 13), but also curtailment reduction from RES power plants (Fig. 14).

Figs. 15–16 show the results of this parametric analysis for P2L scenarios, and the same general considerations apply as for SNG scenarios.

It is worth observing that P2G/P2L options only become favourable if hydrogen generation can be managed with some flexibility, for example, thanks to hydrogen storage and an increased electrolyser capacity above the minimum. With this regard, Fig. 13 shows that emissions can be reduced with respect to an energy scenario without P2G/P2L only if hydrogen can be stored and electrolyser capacity is 40% higher than the minimum required, in the case of an 87% hydrogenation efficiency.

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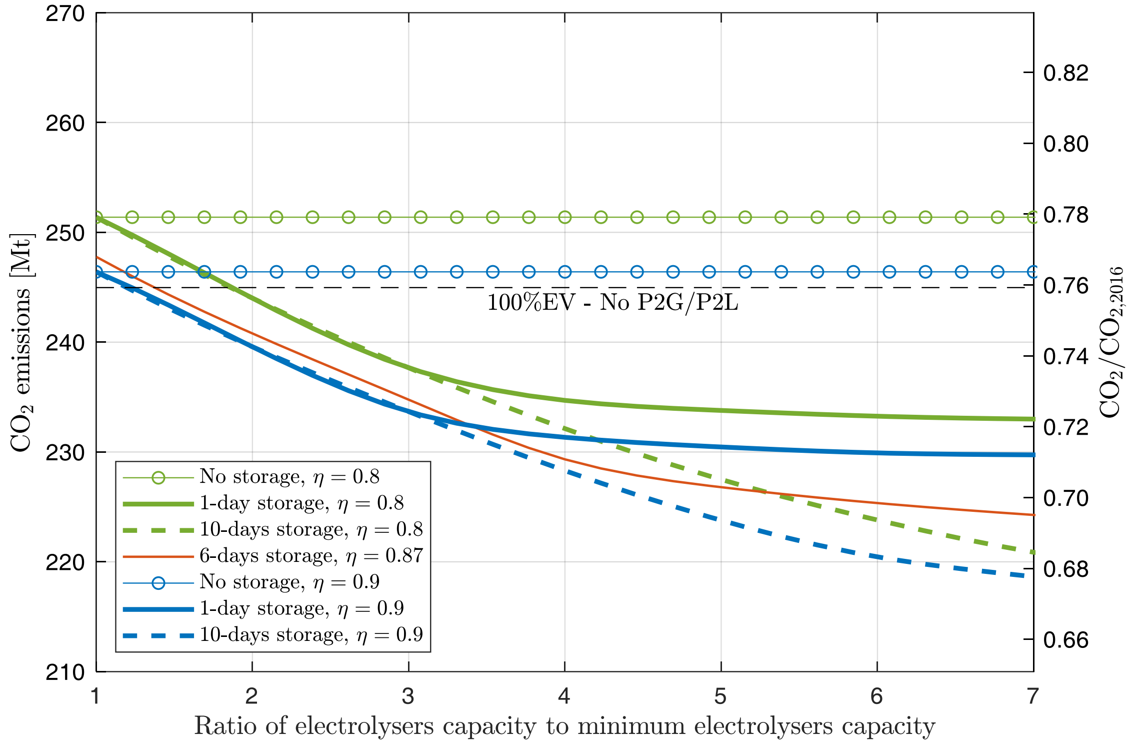

Figure 13. CO_2 emissions for different values of electrolyser capacity, hydrogen storage capacity, hydrogenation efficiency: 7.4×RES, biomass→SNG scenario

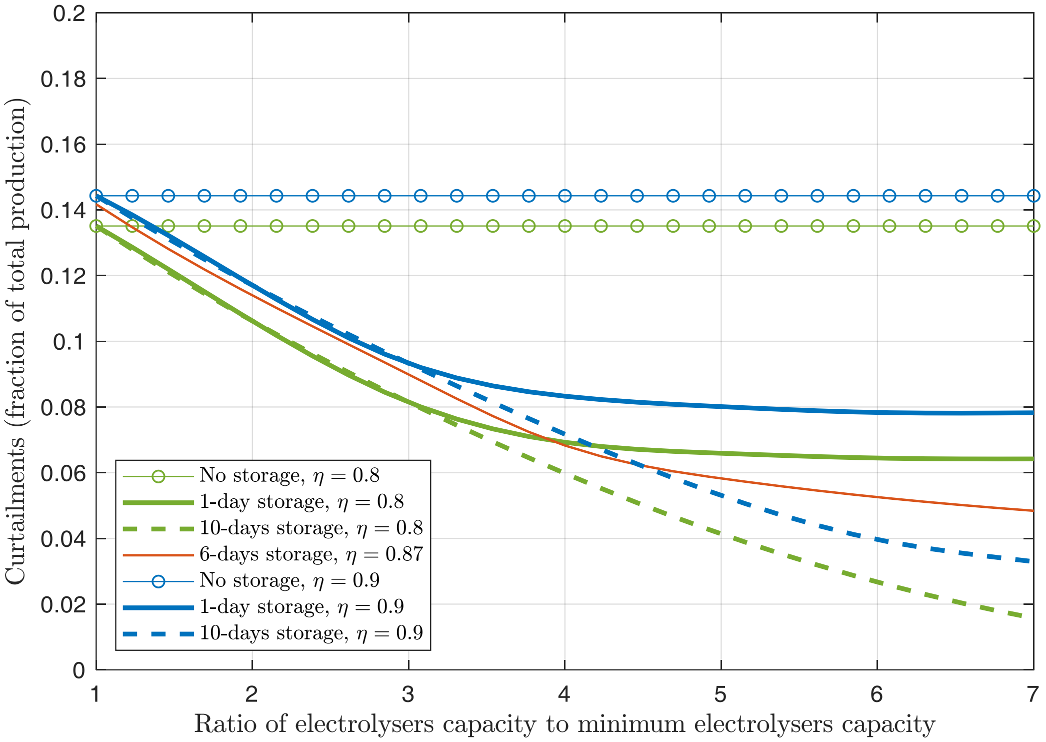

Figure 14. Curtailments for different values of electrolyser capacity, hydrogen storage capacity, hydrogenation efficiency: 7.4×RES, biomass→SNG scenario

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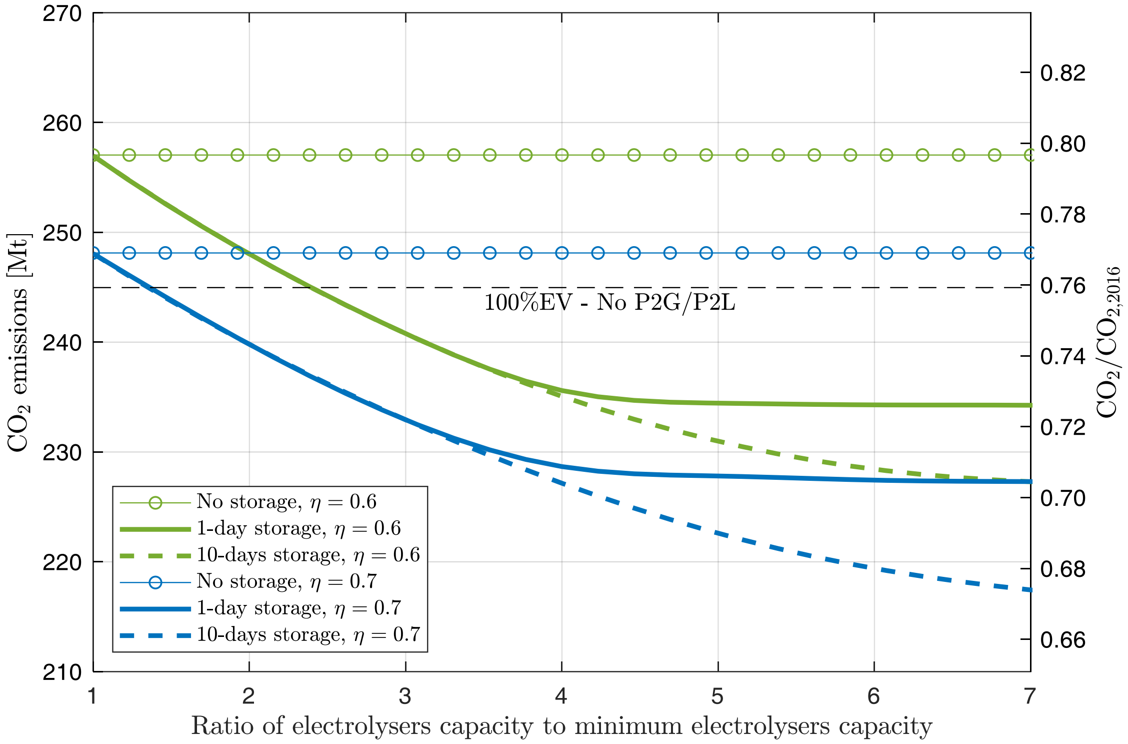

Figure 15. CO_2 emissions for different values of electrolyser capacity, hydrogen storage capacity, hydrogenation efficiency: 7.4×RES, P2L scenario

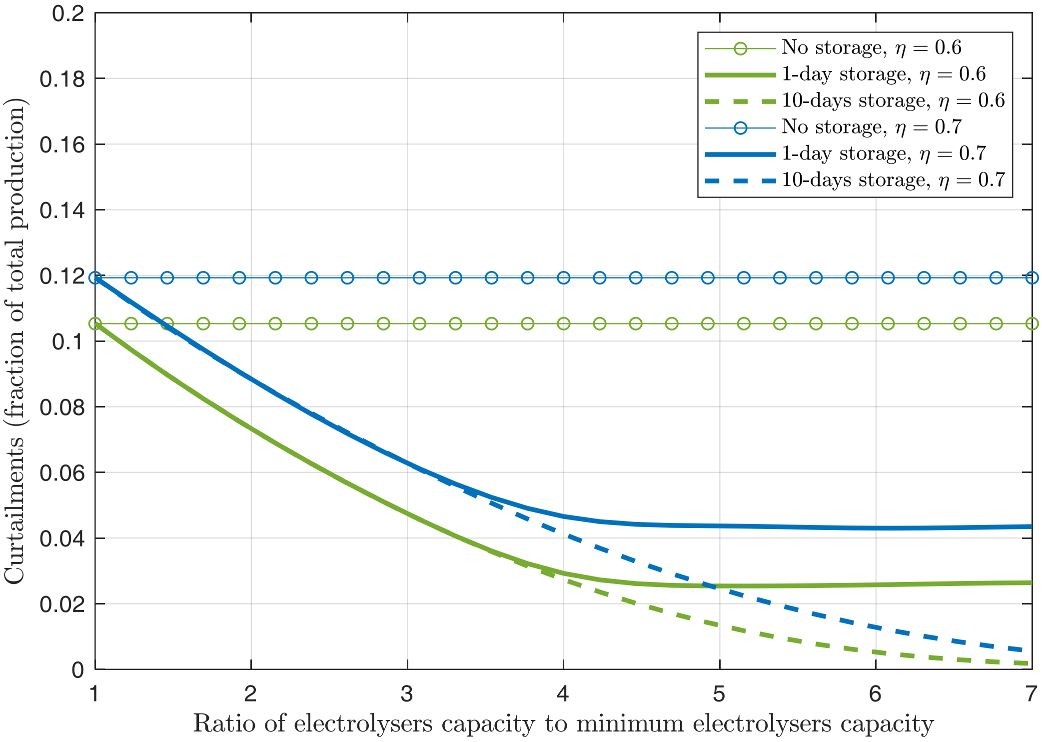

Figure 16. Curtailments for different values of electrolyser capacity, hydrogen storage capacity, hydrogenation efficiency: 7.4×RES, P2L scenario

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3.3 V2G and coal phase-out options

Besides an increase in renewable installed capacity, the National Energy Strategy also foresees, for future energy scenarios, the development of additional electricity storage capacity as well as coal power plants phase-out. Critical energy indicators were derived accordingly and are displayed in Table 20, precisely including V2G as a storage option with vehicles able to feed electricity back to the grid, when needed, and the decommissioning of 8 GW coal power plants capacity.

Both strategies affect only CO_2 emissions related to electricity generation, however, while V2G brings about negligible improvements (around 1%), coal power plants decommissioning has a more substantial impact thanks to the phase-out of the most emissive fuel along with the higher overall average efficiency of conventional generation. However, V2G allows a more efficient usage of renewable sources, resulting in higher RES share and lower curtailments. Overall, in the best case scenario the combined effect of V2G and coal phase-out, together with full electrification of private transport, 7.4×RES and Power-to-Gas systems, leads to a CO_2 emission reduction of 34% as compared to 2016.

Table 20. Results for 7.4×RES and 100%EV including V2G and coal phase-out

	P2L				**Biomass→SNG**			
	Ref.	**V2G**	**No coal**	**V2G+ No coal**	**Ref.**	**V2G**	**No coal**	**V2G+ No coal**
CO_2 emissions [Mt]	235.1	233.3	218.5	216.6	229.3	225.1	217.8	214.5
ΔCO_2 [%]	-27.1%	-27.7%	-32.3%	-32.9%	-28.9%	-30.2%	-32.5%	-33.5%
RES share [%]	56.9%	58.4%	57.3%	58.9%	59.7%	62.3%	59.9%	62.6%
Curtailments [%]	2.7%	0.1%	2.8%	0.1%	6.8%	2.9%	6.9%	2.9%

3.4 Cost analysis

A preliminary cost analysis was undertaken breaking down total annual costs in investments and variable costs according to EnergyPLAN subdivision.

Table 21 reports cost composition at 7.4×RES and 100%EV, for the different analysed scenarios. Set to 100 total costs for the reference case, variable and investment costs were normalized accordingly:

$$C_{i\,norm} = C_i / C_{tot\,2016} \times 100 \quad (4)$$

Variable costs are higher than investment costs in all the different scenarios, mainly due to the relatively long investment period (20–25 years) and their reduction is in the range 14–20% as compared to base case scenario. In terms of CO_2 emissions costs, Biomass→SNG shows the minimum value for the same reasons as described in the paragraphs above. Investment costs variation is at its highest for the least efficient processes, as in Biogas SNG and Biomass P2L. The increase in investment costs is effectively offset by a reduction in variable costs leading to an overall increase in total annual costs between 2 to 6% in Biogas→SNG and Biomass P2L scenarios and negligible variation for Biomass→SNG. These results are in line with a previous study concerning the overall EU28 region [51]. Overall, Biomass→SNG not only leads to the least emissions and curtailments among the proposed P2G/P2L scenarios but also proves to be the best economic option.

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Table 21. Total, investments and variable normalized costs at 2016 (base case) and 7.4×RES at 100%EV

	Base case 2016	**No SNG/P2L**	**Biogas→SNG**	**P2L**	**Biomass→SNG**
Variable costs	76.83	62.39	61.21	66.37	63.29
of which CO_2 emissions costs	12.87	9.90	9.73	9.37	9.14
Investments and O&M	23.17	29.46	40.40	40.06	36.50
Total costs	100.00	91.84	101.61	106.43	99.79

4 CONCLUSIONS

In high-RES energy scenarios and under a Smart Energy System perspective, the implementation of P2G/P2L technologies allows shifting potential RES surplus towards other sectors than electricity generation and, through the production of synthetic natural gas or electrofuels, ultimately leads to a reduction in CO_2 emissions in the heavy transport sector where EV cannot penetrate, by absorbing, at relatively moderate costs, the otherwise-curtailed renewable power.

With particular reference to the Italian case, CO_2 emissions can be reduced by nearly 30% with respect to 2016 when P2G technologies convert biomass to SNG covering approximately 30% of total gas demand, if RES capacity is increased about sevenfold and EV completely replace conventional vehicles in the private transport sector.

Under the assumption that EV may eventually be cost-competitive with conventional vehicles, the rise in investment costs combines with a reduction in variable costs leading to a negligible change in total costs.

Among the most important operating and design parameters in the P2G/P2L pathways, hydrogenation efficiency only plays a minor role, while hydrogen storage and electrolyser capacity have a remarkable influence, highlighting the importance of flexibility in hydrogen generation so as to exploit potential RES generation to the maximum possible extent.

These results can be extended from the Italian case to all those national energy systems characterised by significant emissions in the transport sector and high RES potential: in this case, P2G/P2L technologies can be highly beneficial, provided that electricity consumption for hydrogen production can be managed flexibly.

With a view to maximizing RES deployment, future works will investigate the integration of electricity storage in the energy system as well as a deeper electrification of the heating sector, aiming to define an optimal technology mix representing the best trade-off between costs and CO_2 emissions. Different solutions for CHP plants operation in the context of high RES penetration should also be investigated.

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