Opportunities for Power-to-Hydrogen 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 energy power generation and load curves, along with the need for grid stability, may lead to substantial curtailment when potential power generation exceeds electricity demand. In this respect, the surplus from renewable energies can be exploited to produce hydrogen via electrolysis. This concept is referred to as “Power-to-Gas”, often further categorized as “Power-to-Hydrogen”, and is rapidly emerging as a promising measure in support of a renewable energy penetration that allows the decarbonisation of energy generation without affecting grid reliability.

This study evaluates the impact of Power-to-Hydrogen systems on future CO_2-reduced scenarios, characterized by increasing shares of renewable energies and electric vehicles. Results assess the synergy between power-to-hydrogen technology, renewable energy penetration and sustainable mobility in terms of CO_2 emissions, curtailments and costs.

KEYWORDS

Large-scale RES, P2H, EV, EnergyPLAN, CO_2 emissions reduction.

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 80% by fossil fuels [1]) while reducing the level of greenhouse gases (GHG) 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 2015, followed by transportation sector responsible for 24% of world CO_2 emissions [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]. Indeed, RES contribution in power supply has grown 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, leading to a foreseen RES share of total global electricity production as high as 57–71% at 2050 under the most aggressive CO_2 emissions reduction scenarios [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]. Moreover, RES fluctuation require conventional power plants to operate at partial load under lower efficiency and capacity factor. 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 [6].

Furthermore, generally speaking, RES supply does not directly provide for non-electric needs such as heat and transportation that currently rely heavily on fossil fuels. With this respect, a previous study has been conducted to assess to what extent RES may provide energy for the transport sector when consumption is shifted from fossil fuel to electricity by means of electric vehicles (EV) replacing conventional cars for private transportation [7]. Despite the entire replacement of conventional vehicles fleet and RES capacity increased up to ten times as compared to 2015 level, results show that CO_2 emissions can only be reduced by 20% due to the significant fossil fuel consumption in heavy transport and RES curtailments, that inevitably occur at high renewable installed capacities.

Among the measures to tackle unbalances and capacity adequacy issues associated with RES fluctuating power, electricity energy storage systems are often regarded a promising technology within a smart grid context [8]–[10] along with flexible electricity demand [11], [12] and transmission grid expansion [13]. State-of-art solutions are still not sufficiently effective or integrated, bring about significant costs [14]–[16] or have to deal with environmental impact [17] and scarce public acceptance [18].

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 RES deployment in different energy sectors through a holistic approach [19].

In this regard, a particularly relevant research field involves converting the otherwise-curtailed surplus from renewable electricity in the form of a gas, providing negative balancing power for hydrogen and oxygen production via electrolysis. This technology is referred to as "Power-to-Gas" (P2G), often further categorized as "Power-to-Hydrogen" (P2H) and 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

[20]–[22]. In fact, hydrogen resulting from electrolysis can be injected into the natural gas grid, either directly (up to a limited volume fraction) [16] or after being subjected to a methanation process for *syngas* production, or deployed for electrofuels production in the transport sector (so-called “Power-to-Liquid”, P2L) [23]. 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 [24]–[26]. Moreover, electrofuels can be directly integrated into existing infrastructure, without particular technical or economic constraints [27]. This study aims to analyse to what extent the surplus of RES power can be positively exploited for hydrogen production for the Italian case, under progressively increasing penetration of both RES in the electricity generation and EV in the transport sector. Different scenarios have been modelled with the help of EnergyPLAN software according to the usage of hydrogen within the energy system. Different processes for syngas production are assumed in which hydrogen combines with either biomass-derived syngas or biogas. Results have been compared with respect to relevant indicators: CO_2 emissions, RES penetration curtailments and annual costs.

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 [7], [28].

The analysis has been 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 sectors [29].

Base case scenario modelling

For greater clarity, the main parameters used in the previous works have been herein recalled. Table 1-Table 4 and Table 5-Table 7 show data used for demand and supply section respectively, displaying values and relative sources. In particular, as regards electricity supply, the software requires CHP plants to be partitioned in three different groups depending on their size. Typically, large CHP plants, able to operate in electricity-only mode, belong to Group 3, whereas Group 2 involves CHP plants working in back-pressure mode. All CHP plants have been included in Group 2 (referred to as CHP2), while Group 3 (named PP1) is assumed to be made up of both large CHP plants (typically combined cycle and condensing power plants) and conventional power plants. Group1 refers to district heating boilers only. EnergyPLAN requires also hourly distributions to perform simulations over the year; sources used are displayed in Table 8. With respect to previous studies, this analysis includes a more accurate import/export and heat demand distribution based on the latest actual available data.

Table 1. Electricity loads at 2015

	Consumption [TWh/year]	Source
Electric cooling	13.1	[30], [31]
Electricity for heat pumps (individual)	18.4	[32]
Electric heating (individual)	10.6	[30]
Elec. for transport	10.9	[33]
Other electricity load	230.0	[34]
Total production	***283.0***	
Import	50.9	[35]
Export	-4.5	[35]
Total domestic supply	***329.4***	

Table 2. Fuel consumption and efficiencies for individual heating at 2015

	Consumption [TWh/year] (Source: [36])	Efficiency (Source: [37])
Coal boiler	-	-
Oil boiler	30.5	0.83
Ngas boiler	261.0	0.84
Biomass boiler	72.2	0.75

Table 3. Transport sector fuel consumption at 2015 *(Source:*[33]*)*

	Consumption [TWh/year]
JP (Jet Fuel)	0
Diesel	270.1
of which biodiesel	*13.3*
Petrol	95.6
of which biopetrol	*0.3*
Natural gas	12.6
LPG	21.1
Electricity	10.9

Table 4. Industry and various sector fuel consumption at 2015 *(Source:* [36]*)*

	Industry [TWh/year]	Various [TWh/year]
Coal	14.8	0
Oil	71.0	30.0
Ngas	109.2	13.0
Biomass and waste	7.7	0

Table 5. Power plants capacity and efficiencies at 2015 *(Source:*[34],[37]*)*

	Capacity [GW]	η_{el}	η_{th}
PP1	66.9	0.42	
CHP2	26.6	0.40	0.25
Aux. boilers	18.1		0.90

Table 6. Power plants fuel consumption at 2015

	PP1 [TWh/year] (Source: [34])	CHP2 [TWh/year] (Source: [36])
Coal	113.9	7.8
Oil	9.0	43.3
Natural gas	244.5	164.8
Biomass	65.1	38.4

Table 7. RES capacity (GW) at 2015 *(Source:*[34]*)*

	Capacity [GW]
Onshore wind	6.3
Offshore wind	-
Photovoltaic	10.9
River Hydro	4.9
Dammed Hydro	18.7
Geothermal	0.8
Nuclear	-

Table 8. Sources used for hourly distributions

Electricity demand	[38]
Fixed Import/Export	[39]
Heat demand	[40]
Cooling demand	[37]
Electricity for transport	[37]
Wind	[34]
Photovoltaic	[34]
River Hydro	[34]
Geothermal	[37]

Base case scenario was also validated against critical indicators with respect to 2015 ensuring a variation below 2.8 %.

Table 9. Model validation with respect to 2015 actual data

	Model	*Actual*	*Source*
CO_2 emissions [Mt]	332.22	330.75	[41]
TPES [Mtoe]	145.70	146.00	[41]
RES electricity [TWh]	89.88	89.51	[34]
PP1 electricity [TWh]	197.5	192.05	[34]

Future scenarios modelling

The aforementioned authors' studies 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. Transport demand (as in km/year, driving habits and number of total private vehicles), electricity (excluding demand for future EV), individual heating and cooling demand as well as installed power for conventional plants, remain unchanged with respect to 2015. In the simulated scenarios, intermittent RES maximum overall power generation was parametrically increased up to ten times as compared to the base case scenario, taking also into account potential limits for wind technology.

Table 10. Maximum power from intermittent RES

	Max power at 2015 [GW]	Max Capacity [GW]
Onshore wind	6.3	20.0
Offshore wind	-	10.0
Photovoltaic	10.9	99.6
Concentrating solar	-	42.7

The impact of private transport only within the whole transportation sector was assessed and conventional vehicles were further divided into different categories according to their engine fuel type and displacement capacity. It was assumed a linear decrease for petrol and diesel cars in each category and a simultaneous progressive replacement by EV (from the corresponding category). For each EV penetration scenarios, two different options were analysed according to the implemented battery charging strategy:

- Dump charge: EV charge without regulation, depending on the demand or habits of the drivers;
- 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.

Modelling power-to-hydrogen options

Previous results showed that, despite a complete replacement of EV in the private transport sector, consumption of fossil fuel still exists in the heavy transport (where EV cannot penetrate) as reported in Table 11 and related emissions still represent 16% of the total. Moreover, despite an increase in RES capacity ten times higher than 2015 level, curtailments were as high as 31% of total electricity production even with a total penetration of EV charged using a smart charge option [28].

Table 11. Fossil fuel consumption in heavy transport at 2015

Fuel	[TWh/year]
JP (Jet Fuel)	7.5
Petrol	14.7
Diesel	129.9

With this respect, solutions have been investigated in this study 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. Two main alternatives for syngas production have been assumed, according to the options available in EnergyPLAN:

- Methanation of biogas (scenario labelled as “EV(A)”);
- Hydrogenation of syngas from biomass gasification (“EV(B) ”).

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

- Syngas injected in the grid gas and replacing natural gas (Scenarios labelled as “Grid”);

- Syngas used for electrofuels production replacing fossil fuels in heavy transport sector (Scenario “EF”).

Operating parameter for biomass gasification plant are listed in Table 12, while Table 13 displays hydrogen shares required for hydromethanation processes. Such parameters are in line with literature values referring to the process of glucose gasification through anaerobic digestion and cellulous steam gasification [42]; the products of these processes have been respectively used for biogas (EV(A)) and syngas (EV(B)) hydrogenation methods.

Table 12. Gasification plant operating parameters

Parameter	Efficiency
Steam share	0.95
Steam efficiency	0.94
Cold gas efficiency	0.90

Table 13. Hydromethanation methods operating parameters

Method	Efficiency	Hydrogen share
Biogas hydrogenation	0.94	0.52
Syngas hydrogenation from biomass gasification	0.95	0.36

Electrofuels are produced via chemical synthesis assuming a process efficiency of 0.8 for electropetrol and electrodiesel diesel and 1 for electroJP production, according to values used in a case study for the Italian energy system, developed within the EU-funded Heat Roadmap Europe project [37]. Electrofuel production is assumed to gradually increase with EV penetration until a complete replacement of fossil fuel in the heavy transport.

Electrolysers have been designed with an efficiency equal to 0.73 and an installed capacity equal to double the average power required to guarantee the annual hydrogen production for syngas/biogas hydrogenation processes estimated on the amount of electrofuel needed. It is worth mentioning that in “Grid” scenarios the amount of syngas injected in the gas grid corresponds to the syngas required for electrofuel production in the equivalent “EF” alternative.

Hydrogen storage has not been included in the study thus basically assuming a simultaneity between hydrogen production through electrolysers and its consumption for syngas hydromethanation processes. Including the option of a storage system would potentially bring benefits to the energy system possibly resulting in electrolysers size reduction and an enhancement of their operating conditions providing also the opportunity to better exploit RES electricity surplus allowing a decoupling between production and demand. However, the implementation of a hydrogen storage system in support of electrolysers production is not essential for the purpose of this study that focuses on the opportunity for RES deployment towards other usage than electricity generation, transportation in this particular case. Furthermore, besides Pumped Hydro, whose capacity cannot be increased significantly in developed countries such as Italy, fully developed and commercially mature technologies for grid-scale energy storage are not currently available (indeed, it is a hot research topic). Thus, an accurate estimation of technical specifications and costs would be hard to derive accurately Nonetheless, a follow-up of this work will investigate the integration of electricity and hydrogen storage in the energy system including also a possible optimisation of storage operation management.

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 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 and biomass gasification plants. Conventional vehicles and EV average purchasing price as well as costs related to hydromethanation processes have been also reported. Road vehicles costs have been inputted as a weighted average of actual manufacturers' price for each category as displayed in Table 16; EV medium category is assumed made up of 30% BEV and 70% PHEV to be in line with future projections with respect to EV fleet composition [43]. EV costs refer only to purchase costs and not to total life cycle; for both conventional and electric cars the investment period and the interest rate have been set to 10 years and to 3% respectively. In this revised version of the manuscript, two different options have been provided in regard to EV considering purchasing price unchanged with respect to 2015 level as well as a reasonable 20% price reduction on a medium-long term basis.

Table 14. Intermittent RES related costs *(Source:* [37]*)*

	Investment [M€/MW-e]	**Period [Years]**	**O. and M. [% of Inv.]**
Onshore wind	1.3	20	3.1
Offshore wind	2.4	20	3.0
Photovoltaic	1.3	30	2.1
Concentrating solar	6.0	25	8.2

Table 15. Fuel price *(Source:* [37]*)*

	Price [€/GJ]
Coal	2.6
Fuel Oil	6.8
Diesel Gasoil	9.0
Petrol/JP	9.1
Ngas	6.9
LPG	15.5
Biomass	5.7

Table 16. Road vehicles purchasing costs

	Average price [k€]		
	Petrol	**Diesel**	**EV**
Small	12.0	16.2	29.8
Medium	20.2	20.4	37.0
Large	58.2	58.8	88.3

Table 17. Gas and electrofuel production related costs *(Source:* [37]*)*

	Unit	Price [M€/unit]	Period [year]
Electrolyser	MW-e	2.5	28
Synthetic gas plant EV (A)	MW	0.8	20
Synthetic gas plant EV (B)	MW	0.8	20
Chemical synthesis	MW	0.6	20
Biogas plant	TWh/year	239.7	20
Gasification plant	MW	0.4	25

RESULTS AND DISCUSSION

Different scenarios have been compared with respect to critical indicators as in CO_2 emissions, RES penetration, energy curtailments and annual costs. Table 18 lists results for the different options evaluated for both syngas production methods (EV (A) and EV (B)) and syngas destination (EF and Grid) at RES overall maximum capacity (172.3 GW). As for CO_2 emissions, variations are evaluated with respect to 2015 scenario.

EV (B) scenarios lead to the highest values in terms of CO_2 emissions reduction (-28.8% and -29.4%). Syngas destination affects CO_2 emissions; in fact, despite an additional efficiency for eletrofuel production, when syngas replaces fossil fuel for transportation (EF scenarios), instead of natural gas (Grid scenarios), slightly more beneficial results can be obtained due to the higher emission factors of diesel and petrol as compared to natural gas.

RES share and curtailments only change according to the method of syngas production, regardless of syngas end purpose within the energy system. Curtailments are the lowest for EV (A) option, i.e. 21.8%, which compares with 28.0% if EV (B) solution is adopted.

Table 18. CO_2 emissions variation, RES share and curtailments at different EV penetration

ΔCO_2	**0%EV**	**20%EV**	**40%EV**	**60%EV**	**80%EV**	**100%EV**
EV (base)	-5.6%	-8.5%	-11.7%	-14.8%	-17.8%	-20.8%
EV (A) - Grid	-5.6%	-10.2%	-14.8%	-18.9%	-22.6%	-25.9%
EV (A) - EF	-5.6%	-10.3%	-15.1%	-19.3%	-23.1%	-26.6%
EV (B) - Grid	-5.6%	-10.4%	-15.4%	-19.5%	-24.5%	-28.8%
EV (B) - EF	-5.6%	-10.5%	-15.6%	-19.8%	-25.0%	-29.4%
RES share[% of total electricity production]						
EV (base)	51.2%	52.5%	53.6%	54.6%	55.5%	56.3%
EV (A)	51.2%	54.1%	56.0%	57.2%	57.6%	57.6%
EV (B)	51.2%	53.6%	55.5%	56.1%	57.7%	58.3%
Curtailments [% of total electricity production]						
EV (base)	79.9%	72.9%	66.6%	60.8%	55.5%	50.6%
EV (A)	79.9%	62.4%	48.4%	37.3%	28.7%	21.8%
EV (B)	79.9%	65.4%	53.4%	43.8%	35.0%	28.0%

As displayed in Figure 1, when EV replace entirely the fleet of conventional vehicles and RES capacity is set to its maximum level, CO_2 emissions may be reduced down to 234.5 Mt, basically reaching 233.6 Mt (the value required by 2017 National Energy Strategy for 2030), in the case of hydrogenation of syngas resulting from biomass gasification. Smaller emissions reductions are achieved when hydrogen is used for biogas methanation, as a consequence of the lower system efficiency combined with the higher share of H_2 used in the process. In fact, when surplus of RES power is not available, or relatively small, or partially adsorbed by the increased electricity demand from EV, conventional power plants are required to provide the additional electrical power for hydrogen production. Figure 2 displays, for 100%EV (base) and 100%EV (A) - EF scenarios, at RES capacity equal to 2015 level, how electricity production from conventional power plants increases when electrofuel consumption arises, inevitably resulting in higher CO_2 emissions.

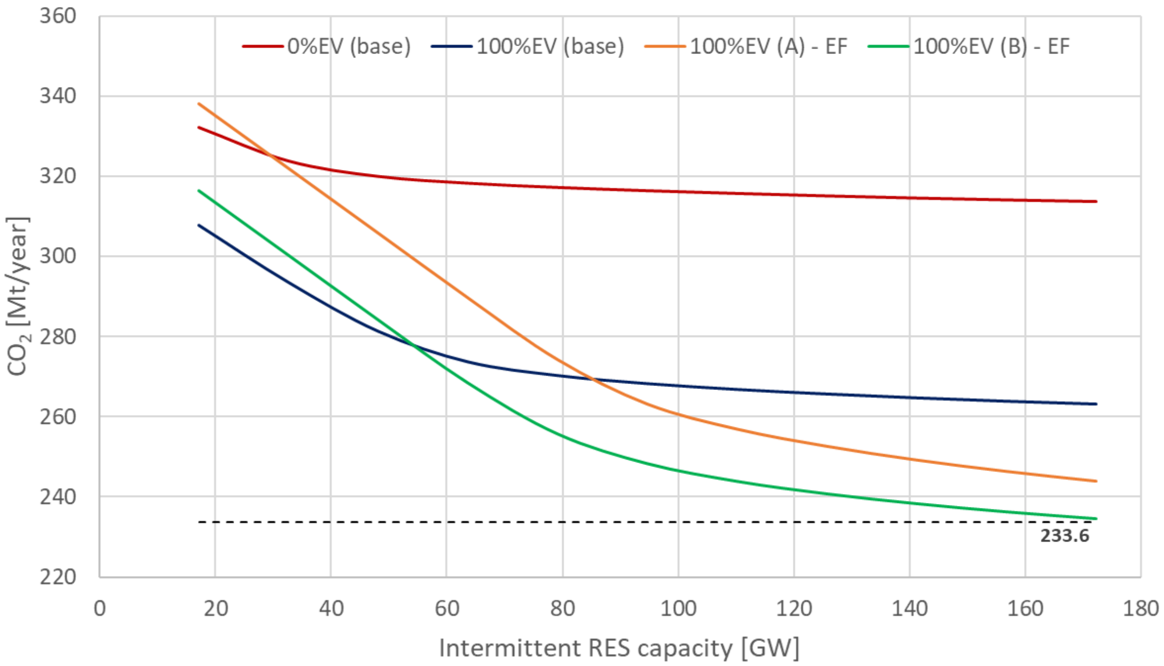

Figure 1. CO_2 emissions for increasing intermittent RES capacity and electrofuel production

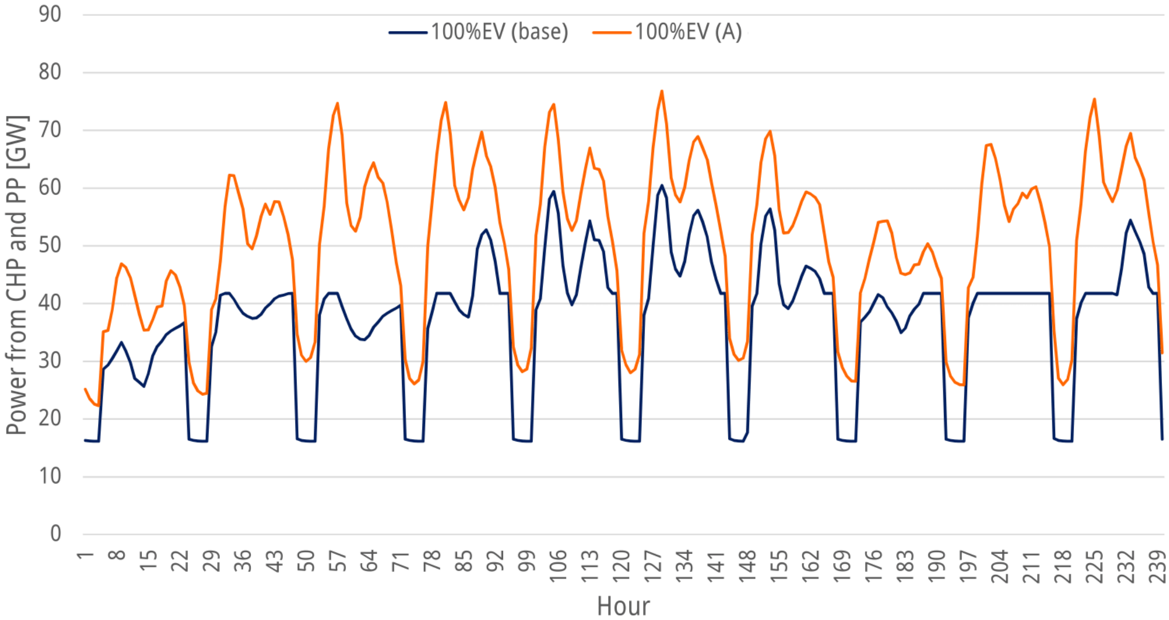

Figure 2. Production from conventional power plants at minimum RES capacity

However, the growth in electricity demand related to electrofuel production becomes favourable 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-contemporaneity between intermittent RES potential generation and electricity demand calls for additional production from conventional power plants thus curbing reduction of CO_2 emissions. Figure 3 and **Errore. L'origine riferimento non è stata trovata.** compare electricity demand along with curtailments and electricity generation for EV (base) and EV (A) - EF respectively, at RES maximum capacity during approximately ten days of spring when 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 Figure 4.

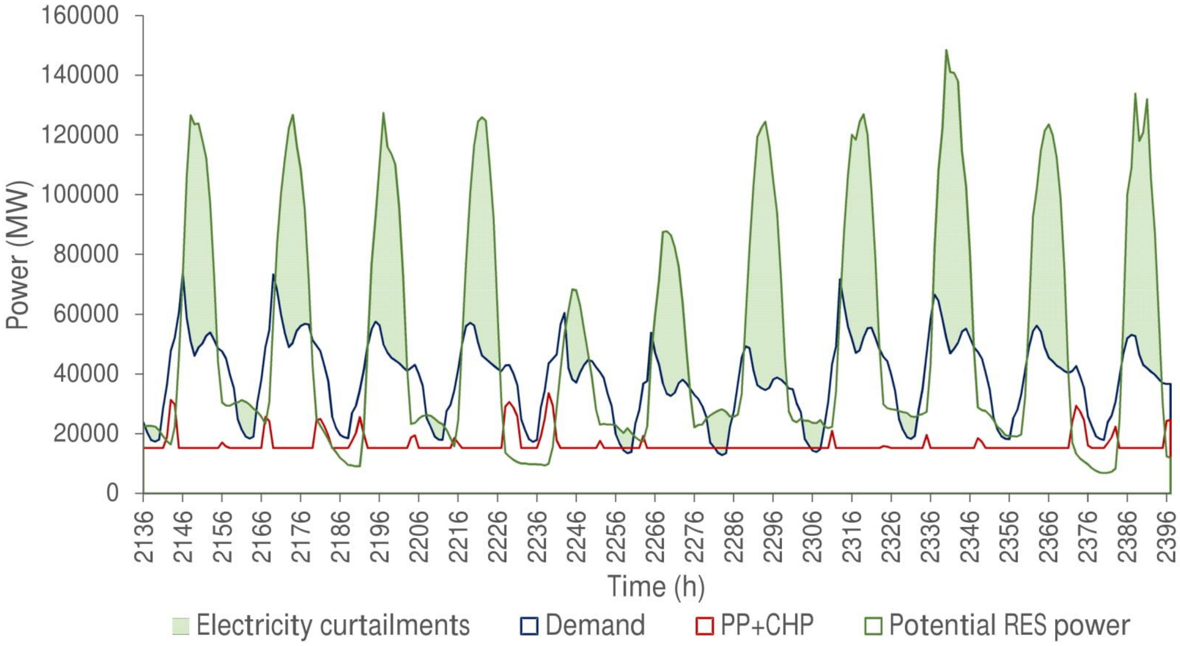

Figure 3. Power generation and demand at maximum RES capacity and 100%EV (base)

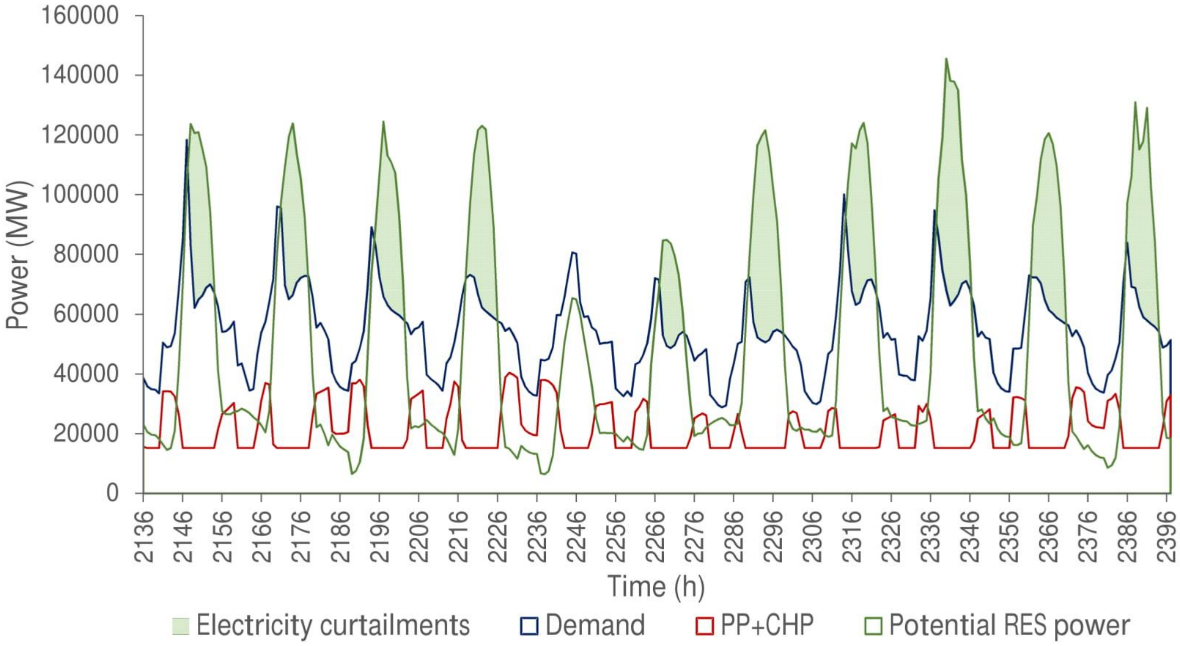

Figure 4. Power generation and demand at maximum RES capacity and 100%EV (A)

CO_2 emissions related to 100%EV (B) – EF scenario, solution that brings about the highest reduction, have been disaggregated according to energy sectors as displayed in Figure 5 and Figure 6 for EV (base), and EV(B) – EF respectively. In line with what was previously mentioned for EV (A) case, besides a significant reduction in the non-private transport sector due to electrufel consumption, emissions from electricity generation still register an increase (from 94.2 Mt to 105.9 Mt).

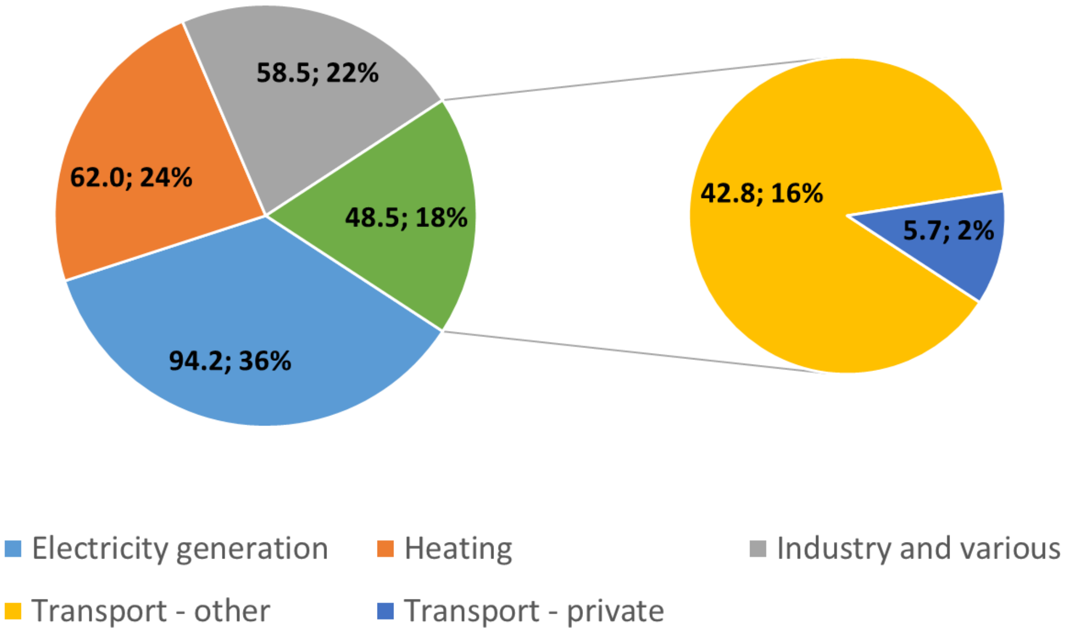

Figure 5. CO_2 emissions by sector at maximum RES capacity – 100%EV (base)

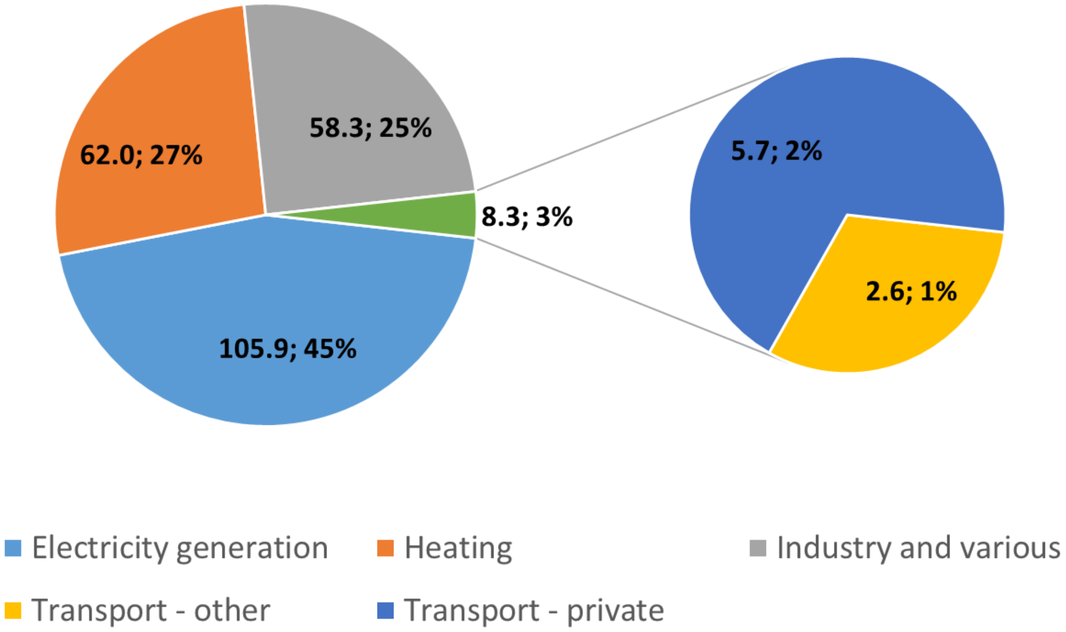

Figure 6. CO_2 emissions by sector at maximum RES capacity – 100%EV (B) – EF

RES share and curtailments are shown in Figure 7 and Figure 8 against increasing RES capacity and electrofuel production with EV totally replacing conventional fleet for private transportation. The electrification of the energy system, due to EV penetration first and to electrofuel production afterwards, causes curtailements, responsible for the plateau of RES share curves, to arise at progressively higher RES capacity and to overcome the desired threshold of 55% RES share reported in the National Energy Strategy.

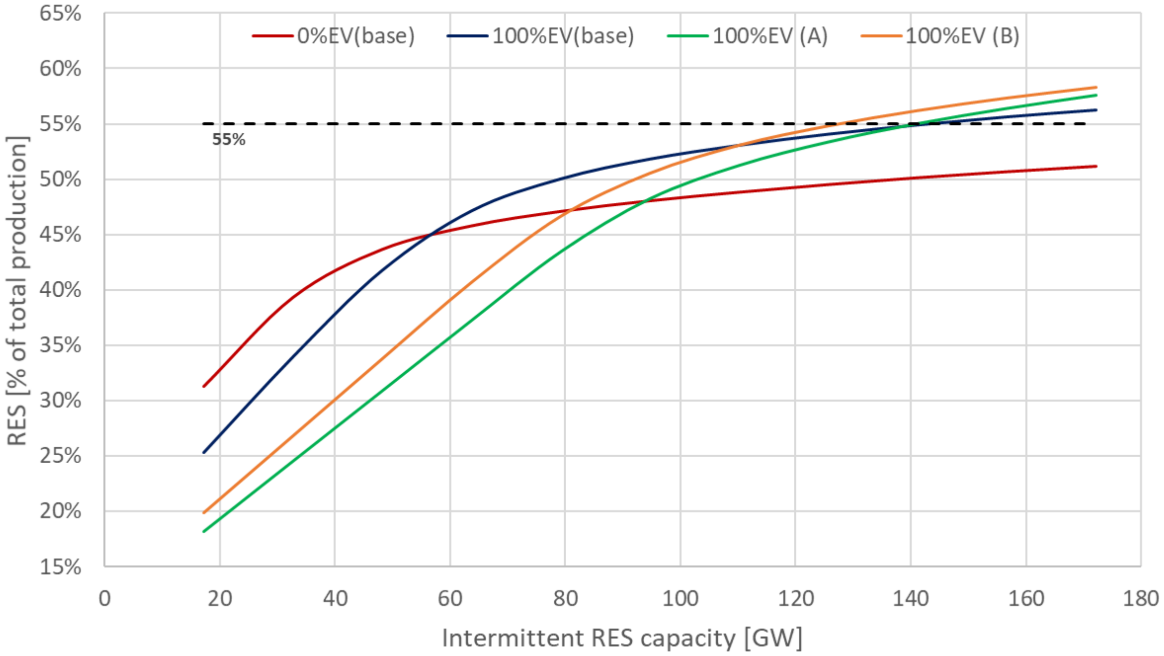

Figure 7. RES share for increasing intermittent RES capacity and electrofuel production

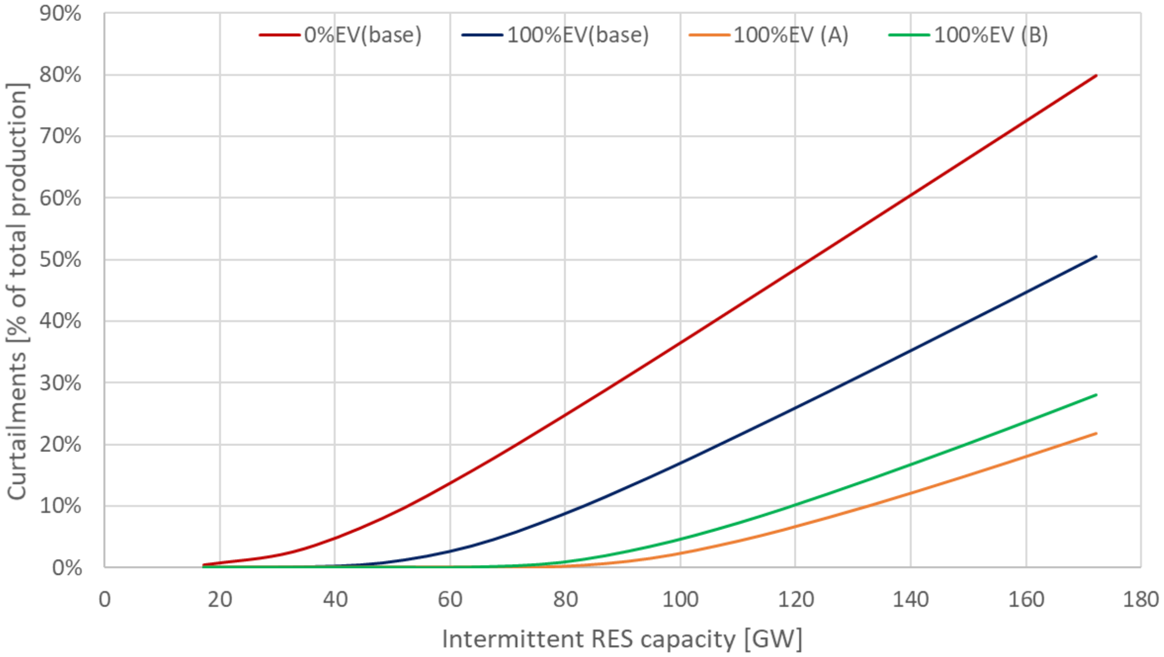

Figure 8. Curtailments for increasing intermittent RES capacity and electrofuel production

A preliminary cost analysis has been undertaken breaking down total annual costs in investments and variable costs according to EnergyPLAN subdivision. Percent variations refer to 2015 scenario as follows:

$$\Delta C_k = \frac{C_k - C_{2015}}{C_{2015}} \tag{1}$$

where *k* represents the EV share.

Table 19 reports the above-mentioned costs variations at different EV share for different implemented options for syngas production and end use within the energy system at the highest RES capacity.

Costs are highly affected by EV purchasing price under the conservative assumption that this latter remains unchanged with respect to current 2015 value. As a result, at maximum RES capacity and EV penetration, investments costs for EV (A) and EV(B) options register a considerable increase, higher than 140% for P2H scenarios as compared to base case. However, the resulting increase in total annual costs is partly mitigated by the reduction in variable (as in fuel) costs. 100%EV (B) scenarios entails an overall annual cost increase around 85%, with a reduction in fuel costs in the range 27-28%. Due to the larger amount of hydrogen produced via electrolysis in EV (A) scenarios, variable costs see a higher reduction that however entails an increase in electrolysers installed capacity that affects investment costs in turn, thus resulting in an overall slight increase of total annual costs.

Table 19. Total, investments and variable costs percent variations at different EV penetration

ΔC_t[%]	**0%EV**	**20%EV**	**40%EV**	**60%EV**	**80%EV**	**100%EV**
EV (base)	35.4%	44.3%	53.1%	61.9%	70.8%	79.7%
EV (A) - Grid	35.4%	45.6%	55.8%	66.1%	76.6%	87.1%
EV (A) - EF	35.4%	45.8%	56.1%	66.5%	77.1%	87.8%
EV (B) - Grid	35.4%	45.2%	54.9%	65.0%	74.7%	84.6%
EV (B) - EF	35.4%	45.4%	55.2%	65.4%	75.3%	85.3%
ΔC_i[%]						
EV (base)	56.7%	71.9%	87.2%	102.4%	117.7%	132.9%
EV (A) - Grid	56.7%	74.7%	92.8%	110.8%	128.8%	146.9%
EV (A) - EF	56.7%	75.0%	93.3%	111.6%	130.0%	148.3%
EV (B) - Grid	56.7%	73.5%	90.4%	107.2%	124.0%	140.9%
EV (B) - EF	56.7%	73.8%	90.9%	108.0%	125.2%	142.3%
ΔC_v[%]						
EV (base)	-6.8%	-10.5%	-14.6%	-18.4%	-22.2%	-26.0%
EV (A) - Grid	-6.8%	-12.1%	-17.6%	-22.6%	-27.2%	-31.5%
EV (A) - EF	-6.8%	-12.3%	-17.9%	-23.0%	-27.7%	-32.1%
EV (B) - Grid	-6.8%	-10.9%	-15.3%	-18.8%	-23.3%	-27.0%
EV (B) - EF	-6.8%	-11.1%	-15.6%	-19.2%	-23.8%	-27.6%

The impact of EV price reduction has been also evaluated; with reference to EV (B) – EF scenario two different options have been implemented in which EV purchasing cost registers a 20% reduction as compared to 2015 level and when it equals conventional cars average purchasing price. Results are displayed in Table 20 showing that, at 100%EV, investments costs can be basically halved when EV purchasing price is lowered down to conventional vehicles one. In this particular case, the increase in investments costs is only related to P2H-related technologies whose impact is moderate given the relatively long investment period considered (above 20 years).

Table 20. Total, investments and variable costs percent variations with EV price reductions options

ΔC_t[%]	**0%EV**	**20%EV**	**40%EV**	**60%EV**	**80%EV**	**100%EV**
EV (B) – EF (20% price reduction)	35.4%	40.9%	46.4%	52.1%	57.6%	63.2%
EV (B) – EF (conventional car price)	35.4%	35.2%	35.0%	35.0%	34.7%	34.7%
ΔC_i[%]						
EV (B) – EF (20% price reduction)	56.7%	67.2%	77.6%	88.1%	98.6%	109.0%
EV (B) – EF (conventional car price)	56.7%	58.6%	60.4%	62.3%	64.2%	66.0%
ΔC_v[%]						
EV (B) – EF	-6.8%	-11.1%	-15.6%	-19.2%	-23.8%	-27.6%

It is worth mentioning that the modelled scenario implies a certain amount of biomass that can be as high as 153.5 TWh (thus almost doubling the amount of 2015 biomass consumption) when fossil fuel for heavy transport are assumed to be completely replaced and research should be conducted to ensure that such value lies within the sustainable threshold.

In general, the implementation of P2H technologies allows the shift of potential RES surplus towards other sectors than electricity generation allowing also, through the production of electrofuels, a reduction in terms of CO_2 emissions in the heavy transport sector where EV cannot penetrate adsorbing, at relatively moderate costs, the otherwise-curtailed renewable power. Besides the Italian case, those national energy systems characterised by significant emissions in the heavy transport sector may highly benefit from P2H technologies. However, such systems would highly benefit from the implementation of a hydrogen storage option in terms of operating conditions and optimisation of the RES power excess usage. Moreover, the above-discussed data refer to the highest RES capacity taken into account in the analysis. However, as shown in Figure 1, a plateau in CO_2 emissions reduction occurs when RES capacity grows significantly, meaning that similar results can be obtained with a smaller capacity at relatively lower costs. For instance, with reference to 100%EV (B) – EF option, a possible economic optimum that guarantees a good compromise between costs and emissions reduction could be obtained when RES installed capacity reaches values around 110 GW. In such scenario indeed, it is possible to reach a CO_2 emissions reduction of 27% with respect to 2015 level, with an increase in investment cost of 71% (that can be even lowered down to only 21% if EV price is assumed to equalize conventional cars) instead of 85% obtained using a RES capacity of 172.3 GW. In this respect, further research should be dedicated to implement optimization algorithms in the analysis aiming to achieve the best technical, environmental and economic solution with regard to energy system operation.

In addition, other solutions able to exploit the surplus of RES power should be investigated (e.g. electrification of the heating sector) as well as the role CHP plants in the context of high RES penetration.

CONCLUSION

This study aims to evaluate the impact of P2H technology in high RES penetration scenarios characterized by increasing EV share for private transportation. Different end uses for hydrogen within the energy system have been explored for the Italian case and results assessed in terms of relevant environmental, technical and economic indicators. Hydrogenation of syngas from biomass gasification provides higher CO_2 emission reduction and lower costs as compared to biogas hydrogenation solutions. In particular, when RES capacity is set to its maximum level, EV completely replace conventional vehicle fleet for private transportation and syngas allows fossil fuel replacement for heavy transport via electrofuels, CO_2 emissions can be reduced down to 29% with respect to 2015 level. Under the assumption that EV prices may eventually equal conventional cars, the increase in investment costs (66%) combines with a reduction in variable costs (-28%) leading to an overall total costs increase equal to 35%.

For a better RES deployment towards other sectors than electricity generation, a follow-up of this work will investigate the integration of electricity and hydrogen storage in the energy system including also a possible optimisation of storage operation management. Moreover, further research should be carried out to include optimization algorithms in the analysis to properly identify the best compromise in terms of costs and CO_2 emissions for the energy system operation. Also, the electrification of the energy system can be further extended including additional measures that conveniently exploit the excess of RES power, and different solutions for CHP plants operation should be investigated in the context of high RES penetration.

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