Assessing the effectiveness of hydrogen pathways: a techno-economic optimisation within an integrated energy system

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Abstract

With the world still far off-track from averting relentless global warming, and most countries struggling in meeting their self-imposed goals, hydrogen can potentially play a crucial role in tackling the major challenge of decarbonising the global economy in the framework of a sustainable development. Capable to store, carry, and convert energy in a variety of ways, hydrogen can be a versatile tool to exploit fully the potential of renewable energy sources. Using a holistic approach within a techno-economic optimisation, this study aims at analysing quantitatively the effect of different possible energy pathways employing hydrogen, taking the Italian energy system as a case study, assuming a progressive growth in both renewable power generation capacity and electric mobility in private transport. Results confirm the beneficial impact of hydrogen and identify three hydrogen-based pathways in the optimised energy scenarios: production of synthetic natural gas to partially replace natural gas in the grid and both direct hydrogen consumption and production of synthetic liquid fuel in the heavy transport sector. Direct hydrogen injection in the gas grid plays a negligible role instead. At most, CO_2 emissions can be reduced by 49 % within the investigated scenarios, with an increase in annual costs of 8 %.

Keywords: Hydrogen, Power-to-X, EnergyPLAN, Multi-objective optimisation, CO_2 emissions reduction

1. Introduction

Over recent decades, hydrogen has gained ever-increasing attention as a low-carbon energy carrier capable of playing a key role in a clean and secure energy system. It is widely recognised in the literature as a valuable option for the decarbonisation of a variety of sectors [1], including those areas of the energy system where a deep cut to CO_2 emissions is currently hard to deliver, such as long-haul transport, chemicals, iron and

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steel industry. In these applications, hydrogen can be used in its pure form or converted to hydrogen-based fuels, such as synthetic methane, synthetic liquid fuels, ammonia or methanol that, in turn, can be stored, burnt or combined in chemical reactions, similarly to what occurs for fossil fuels. Moreover, hydrogen deployment can be promoted at the beginning as a partial substitute for fossil fuel supply for those infrastructures and end users that already accept it, such as natural gas grids [2, 3].

Though it is true that the use of hydrogen does not entail direct emissions of pollutants nor greenhouse gases, the majority of hydrogen produced nowadays still comes from fossil fuels [4, 5], meaning that its contribution to a sustainable future can be truly effective only provided that cleaner production methods are introduced in the upstream production processes, which could potentially include electrolysis fed from nuclear energy or Renewable Energy Sources (RES). In particular, if Intermittent Renewable Energy Sources (IRES) are considered, hydrogen could potentially represent one of the lowest-cost solutions to foster renewable penetration by allowing renewable energy to be stored (over days, weeks, or even seasonally) in the form of chemical energy, thus tackling issues related to the unavoidable imbalances between intermittent generation and electricity demand [6, 7].

Whether in its pure form or as the basis to produce synthetic "green" fuels, hydrogen has the potential not only to promote a much deeper sector coupling within the energy system [8], by extending the deployment of renewable energy to hard-to-electrify sectors that would be instead conveniently served by chemical fuels, but also to connect regions characterised by an abundant renewable power to energy-hungry areas [9], given that hydrogen-based fuels are easy to transport even over long distances [10, 11].

Nonetheless, several challenges need to be tackled for widespread hydrogen use, mainly related to the high costs required for the profound reconfiguration of the energy system that the forthcoming hydrogen economy entails. In particular, both producing hydrogen from low-carbon energy and developing a hydrogen infrastructure are costly endeavours that could only be pursued under a joint effort by local governments, research organisations and industries to set the basis for an economy of scale allowing cost reductions by promoting mass manufacturing for hydrogen production equipment and delivery infrastructure [6].

Financial commitments to hydrogen economy projects are thus required, but in most countries, they still lack the support they need from a proper policy framework and are hindered by technology uncertainties. As a result, a virtuous cycle for hydrogen can only start if the horizon of energy strategies is broadened to a long-term perspective with clear and irrevocable commitments toward sustainable energy systems. Relying on climate change targets as the single driver for a widespread use of low-carbon hydrogen, it is crucial to establish to what extent hydrogen can provide a beneficial impact on the decarbonisation of the energy system in order to push policymakers and investors to undertake the necessary actions to scale up hydrogen, drive down costs and ultimately reduce the related investment risks for both the governments and the private sector [12].

In this context, research activities become essential to investigate, review, and prove the effectiveness of hydrogen as an energy vector, ranging from its sourcing options, generation processes, storage and distribution technologies, potential demand market, economics, and challenges, with particular focus on the production of hydrogen from RES to speed up the transition to a "hydrogen economy" [13, 14]. The role of specific pathways for hydrogen and its potential for energy system decarbonisation have been analysed in

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the scientific literature focusing on different applications in specific sectors. Regarding the transportation sector, the attention went on Fuel Cell Electric Vehicle (FCEV) adoption [15–17] or synthetic fuels deployment in transportation including a comparison with other low-carbon options [18, 19] or with a particular attention to Power-to-Liquid (P2L) [20]. Looking broadly at the energy system, studies investigated the effect of control strategies on CO_2 emissions, curtailments and costs [21], hydrogen use in the transition towards future smart energy systems as a link between heat and electricity [22] or within a fully integrated renewable energy system [23]. Other aspects included the assessment of the potential role of hydrogen in combined cycles [24].

Within this framework, this study aims to define possible pathways for clean hydrogen usage within the Italian energy system and to quantitatively assess its role in terms of crucial indicators such as CO_2 emissions and RES integration, using the EnergyPLAN software to perform an integrated energy system analysis [25].

Considering Italy as a case study, previous research works already investigated Power-to-Gas (P2G) potentials in long-term scenarios [26] focusing on hydrogen mobility [27, 28] or electrofuels [29] towards a larger integration of renewable power generation. Moreover, when aiming to analyse the effects of a pool of technologies in future scenarios, resorting to an optimisation tool allows the algorithm itself to select a variety of possible configurations acting on different energy sectors, based on specific targets to be optimised, thus avoiding the need to define *a priori* the values of single input parameters. In this regard, research studies, based on the Italian case, have used a Multi-Objective Evolutionary Algorithm (MOEA), coupled with EnergyPLAN, without however including different pathways for potential hydrogen demand within the energy system [30, 31].

As a relevant addition to the literature, this paper aims to quantitatively assess the impact of different technologies relying on green hydrogen to couple different energy sectors and decarbonise the energy system. This assessment is carried out through an energy scenario analysis conducted by means of EnergyPlan, in which the current energy scenario is modified with the introduction of hydrogen generation and its subsequent use in different decarbonisation pathways, besides an increase in RES capacity and the electrification of private transport. Thus, this work investigates and compares possible Power-to-X (P2X) alternatives for Italy, including a techno-economic optimisation that reveals the effectiveness of each specific option for hydrogen end-use under an integrated smart energy system approach to allow the variety of sectors to be synergically interconnected.

The otherwise-curtailed renewable power can be exploited for hydrogen production, which could be alternatively (i) injected into the natural gas grid and consequently used by heat and power generating technologies, (ii) distributed to provide fuel for FCEVs, (iii) converted to Synthetic Natural Gas (SNG) through P2G processes, or (iv) to Synthetic Liquid Fuel (SLF) via P2L technologies. In this analysis, direct hydrogen use in the transport sector is limited to Heavy-Duty Vehicles (HDVs), while FCEVs are not considered in the private transport fleet, which, instead, includes Plug-in Electric Vehicles (PEVs) as substitutes for conventional cars.

2. Methods

The present analysis simulates and compares a set of future scenarios for Italy to evaluate the advantages and drawbacks of different energy system evolution options.

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The assessment starts from a reference case defined and validated with respect to 2017. Techno-economic simulations are performed by means of a MOEA linked to the EnergyPLAN software, aiming to minimise both the CO_2 emissions and the total annual costs based on a set of decision variables and constraints. The adopted methodology is in line with that followed in a recent analysis regarding the impact of the electrification of heating and transport demand for the Italian case [30]; full details and a more extensive description of the base case scenario were developed in a previous study and are available on the open-access repository Zenodo [32].

A variety of sectors are involved in the optimisation process. On the supply side, electricity generation technologies feature a potential large expansion of IRES, as in wind and solar, which comes along with the coal phase-out for conventional generation. On the demand side, a deep reconfiguration of transportation is allowed with PEVs able to replace conventional solutions within Light-Duty Vehicles (LDVs). As concerns freight transportation, FCEVs can potentially substitute diesel trucks and also compete with P2L technologies generating Dimethyl Ether (DME) as a synthetic alternative to diesel consumption in Internal Combustion Engine Vehicles (ICEVs). Other uses of hydrogen are also allowed with the aim of replacing Natural Gas (NG) in the grid; precisely, hydrogen can be injected into the grid either in its pure form or after conversion into a synthetic fuel (see section 2.4 for details). Figure 1 gives a graphical representation of the whole energy system configuration, including the pathways for hydrogen production and usage. The picture highlights the potential role of hydrogen in coupling different energy sectors and in using renewable energy sources more effectively.

A cost development curve is applied to those technologies whose rising deployment is likely to increase their market scale and competitiveness, thus consequently decreasing investment costs under a plausible growth in capacity or production volume.

In the following sections, attention is chiefly given to the description of pathways for hydrogen end uses. Although other sectors are also involved in the overall optimisation process, measures in these areas of the energy system were already described in detail in other studies [30, 33]; thus, they are only recalled briefly herein.

2.1. Electricity generation

Assumptions adopted to outline boundaries for the installed capacity of electricity generation technologies are defined according to Ref. [30], based on current energy policies projections [34] and national available potentials [35, 36]. As for conventional generation, a complete phase-out of coal power plants is implemented, while natural gas plants remain present, with the assumption that available capacity, plant type, and average efficiency are the same as the base case. The installed capacity of IRES (wind and Photovoltaic (PV) power plants) is assumed to increase, so that these are decision variables of the optimisation, as shown in Table 6.

Future costs development refers to the latest available data from International Renewable Energy Agency (IRENA) [37, 38] and to the Heat Roadmap Europe database [39] as concerns the period of investment and O&M costs. Precisely, cost projections for 2030 and 2050 are associated with the predicted installed capacity as provided by the National Energy and Climate Plan [34] and with the national highest potentials [30], respectively. A cost trend can thus be derived as a function of the installed capacity characterising each particular future scenario analysed. Data are summarised in Table 1 for the reference year and for the two simulated years.

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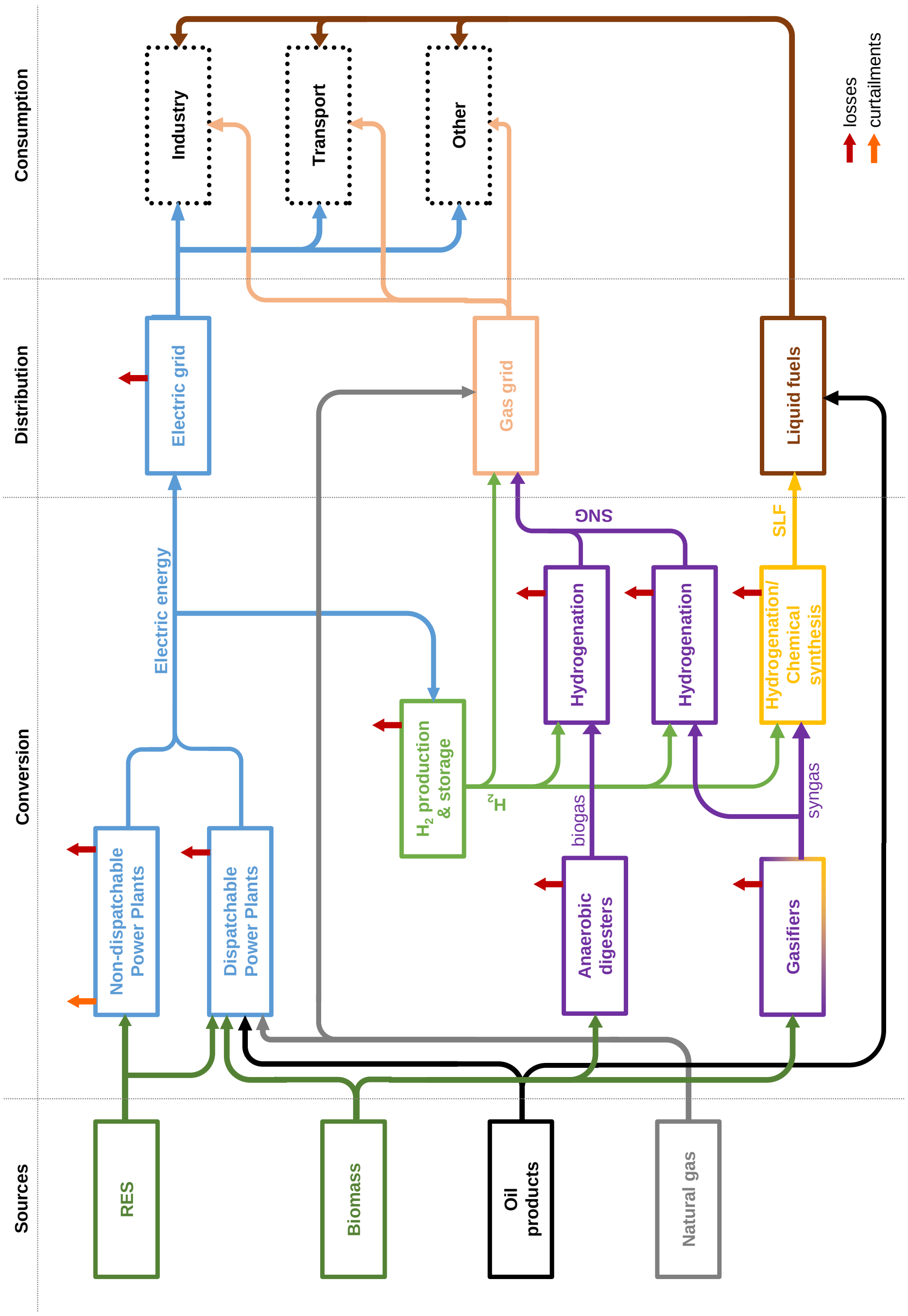

Figure 1: Schematic representation of energy flows in the analysed scenarios.

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Table 1: IRES capacity, investment costs, period of investment, and O&M costs: current values and future projections.

Source	Year	Capacity [30, 34] (GW)	Cost [37, 38] (EUR/W)	Period [39] (years)	O&M [39] (% of Inv.)
PV	2017	19.70	1.08	30	0.88
	2030	50.00	0.74	40	1.28
	2050	200.00	0.43	40	1.32
Onshore wind	2017	9.77	1.33	25	3.21
	2030	17.50	1.20	30	3.27
	2050	68.50	0.89	30	3.40
Offshore wind	2017	0.00	3.87	25	2.00
	2030	0.90	2.85	30	1.90
	2050	3.60	2.49	30	1.88

2.2. Hydrogen production and storage

Solid Oxide Electrolyser Cell (SOEC) technologies are taken into account for water electrolysis, and a constant efficiency of 73% is assumed in this analysis. These units are less flexible than the intermittent nature of renewable power may require to recover the surplus generation on an hourly basis; also, SOEC efficiency varies widely with partial load operation [40], which may be required when coping with intermittent renewable power availability. These aspects are not investigated in this analysis. However, a simulation with a constant 50% efficiency is carried out to estimate the impact of variable efficiency at part-load operation due to the scarce flexibility linked to SOEC complex internal thermal integration.

Each scenario requires a certain minimum electrolyser capacity to guarantee the annual overall hydrogen production (as described in the following sections, hydrogen may be required for transportation and injection in the gas grid). Such capacity can be increased by a factor, identified as electrolyser oversizing factor, to improve flexibility in the hydrogen generation process and allow better exploitation of the available renewable power. Likewise, hydrogen storage capacity is included in the analysis; it is estimated in number of days of storage at the nominal electrolyser capacity. The upper and lower boundaries of such flexibility measures, which are regarded as decision variables, are shown in Table 6.

Electrolysers cost development functions are derived according to data provided by [39], considering the highest level of hydrogen possibly required for transportation, grid injection in pure form, and electrofuels production as the maximum electrolysers capacity, which is associated with the estimated 2050 costs. The capacity in 2030 is conservatively assumed equal to the 20 % of the maximum capacity. Table 2 lists the aforementioned assumptions.

Hydrogen storage costs parameters are set equal to 7.6 EUR/kWh, 25 years and 2.5 % for investment costs, period of investment and O&M costs, respectively [41], in all future scenarios regardless of the capacity level.

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Table 2: Electrolysers capacity, investment costs, period of investment, and O&M costs: current values and future projections.

Year	Capacity (GW)	Cost [39] (EUR/W)	Period [39] (years)	O&M [39] (% of Inv.)
2017	0	2.04	20	3
2030	10.01	0.56	20	3
2050	50.07	0.37	30	3

2.3. Transport sector

Innovations in the transportation sector concern both LDV and HDV. With regard to private transport, a potential substitution of conventional cars with PEV is implemented, up to a complete replacement, taking into account updated features from current vehicle fleets (following the procedure described thoroughly in Refs. [29, 33]). In particular, the average powertrain efficiency for diesel and gasoline vehicles is set at 4.47 and 5.04 l/100km, respectively [42], and at 0.174 kWh/km for electric cars. Transport demand is expressed in terms of vehicle-kilometres and remains unchanged in the simulation; it is evaluated as following:

$$D_{LDV} = n_d \times km_d + n_g \times km_g \tag{1}$$

where n_d and n_g are the number of diesel and gasoline cars, respectively.

It is worth noting that, despite featuring both an electric powertrain, PEVs are kept separate from FCEVs so as to underline the difference concerning the input energy vector powering the vehicle. With respect to PEVs, according to updated projections, Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) are assumed to account respectively for 88 and 12 % of the total PEV fleet [43]. The Learning Rate (LR) for BEVs and PHEVs is set to 15.2 and 10 %, respectively [44], with PEVs accounting for 7.5 million vehicles in 2030 [45].

In this work, for freight transportation in future scenarios, two different decarbonisation options are taken into account and allowed to compete within the techno-economic optimisation framework. Precisely, FCEVs can replace conventional diesel trucks and P2L technologies can be implemented to provide DME as a synthetic substitute of diesel in ICEVs [46].

The overall number of HDVs object of replacement is derived according to the latest data of Associazione Nazionale Filiera Industria Automobilistica (ANFIA) and set to 573 475 units (freight transportation trucks above 3.5 t) [47]. The related current fuel consumption for diesel trucks is set to 7577 $\mathrm{Mt_{diesel}}$ annually, according to the latest Unione Petrolifera (UP) report for the Italian case [42]. Diesel truck efficiency is set to 34.6 litres/100km [48] along with a purchasing price of 110 kEUR [48].

With respect to FCEVs, powertrain specific consumption and costs are set according to Nikola One model [49], i.e. 4.6 kg/100km [50] and 320 kEUR [51]. A LR of 14 % is used for fuel cells, applied to an initial cost of 290 EUR/kW and estimated from the costs variation with the annual production volume displayed in Ref. [52].

Finally, costs related to PEV and FCEV infrastructure are included within the techno-economic optimisation considering costs related to the charging and refuelling stations,

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respectively. As for PEVs, the cost trend is derived from a report developed by Enel Foundation and Politecnico di Milano [53], where costs related to the PEV charging infrastructure are evaluated at both urban and extra-urban scale under increasing penetration of electric mobility.

$$C_{\text{PEVinfrastructure}} = (10^4 \times PEV_{share} + 50)\,\text{MEUR} \tag{2}$$

Infrastructure costs for FCEV are defined considering an increasing utilisation rate for hydrogen refuelling stations up to 80 % at the highest level of hydrogen trucks penetration according to the procedure followed in other reports in the literature [54]. The refuelling station capacity is also assumed to increase from an initial value of 1500 up to 4000 kg/day, while the maximum number of stations is limited to 1000 in the country. A single station's investment cost is derived by applying the correlation between station capacity and investment cost used in Ref. [50].

The discount period for infrastructure investments is assumed equal to 30 years.

2.4. Power-to-gas and power-to-liquid

In this study, the hydrogen-based decarbonisation pathways consider hydrogen to be either injected into the gas grid as it is, or combined with biogas to produce SNG, or combined with biomass-derived syngas to produce either SNG or SLF, as described in Ref. [29] (see Fig. 1). In particular, the P2L option results in the production of DME replacing diesel consumption for HDVs.

The amount of hydrogen injected in its pure form in the gas grid is evaluated considering a blending ratio with respect to natural gas in the range 0–20 % in volume.

The configurations that involve the hydrogenation of gasified biomass to produce SNG and SLF (labelled respectively as "biomass→SNG" and "biomass→SLF") are based on an upper limit for biomass input equal to 108 TWh, according to the overall national availability [55] (see for details Table 6).

Operating parameters for biomass gasification plants and hydrogenation of the resulting syngas are illustrated in Table 3 and 4, respectively, along with the related sources.

Table 3: Biomass gasification plant operating parameters (Sources: [23, 39, 56]).

Steam share (share in relation to biomass input)	σ	0.13
Steam efficiency	η_{steam}	1.25
Cold gas efficiency	η_{cg}	0.90

Table 4: Hydrogenation processes: operating parameters (Sources: [56, 57]).

	Efficiency		Hydrogen share	
	SNG	SLF	SNG	SLF
Biogas hydrogenation	0.83	-	0.50	-
Syngas hydrogenation	0.87	0.60	0.36	0.38

Similarly to processes that involve biomass gasification, SNG can be obtained from biogas hydrogenation (scenarios identified with "biogas→SNG"), considering a maximum

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Table 5: Gas and electrofuel production-related costs [39].

	Unit	Cost (MEUR/unit)	Period (years)	O&M (% of inv.)
Electrolyser	MWe	1.8	15	5
Hydrogen storage	GWh	10.2	30	-
Methanation	MW	0.6	25	4
Liquid fuel synthesis	MW	1.0	25	4
Gasification plant	MW	1.8	20	2.2
Biogas plant	TWh/year	190.2	20	11

national potential biogas production of 8 billion Nm^3. Biogas feedstock price, as in energy crops, manure and other agro-industrial waste, is assumed to vary between 0 and 5.9 EUR/GJ within a parametric analysis [58].

Cost development for biogas and biomass gasification plant was defined starting from Heat Roadmap Europe costs database reporting investment costs as a function of future years. In the absence of data on cumulative plant production in a given year, LRs are derived considering that the highest biogas and gasified biomass production occurs in 2050 and consequently set to 3.7 and 5.3 % respectively for investment costs.

LRs for fuel synthesis plants are derived from are a recent review on production costs for electrofuels [59] and set to 18.8 % for both methane and DME synthesis.

Base costs for P2G and P2L technologies are listed in Table 5.

2.5. Multi-objective optimisation and decision variables

In this study, the authors devised a software tool based on EnergyPLAN [25] to simulate multiple scenarios with a combination of input variables aiming to define a Pareto front of techno-economic optimal solutions. EnergyPLAN was chosen among many energy system models for its good temporal resolution and full cross-sector coverage, among other features [60]. The multi-objective optimisation is carried out by means of the MATLAB® function `gamultiobj` [61], that finds a Pareto front for multiple-objective functions using a controlled, elitist genetic algorithm (a variant of NSGA-II [62]). The MOEA allows finding the best energy mix in terms of selected objectives based on a given set of decision variables. In this case, the objectives to be minimised are the total annual costs and CO_2 emissions.

This section describes the set of decision variables implemented in the optimisation algorithm, the relationship among them, their upper and lower boundaries, and the linear constraints they are subject to. The full list of decision variables used in the optimisation algorithm is given in Table 6, together with their lower and upper boundaries. In particular, decision variables are needed in each energy sector that is modified compared to the reference scenario:

- electricity generation from renewables: variables x_1, x_2, x_3;
- fossil fuel consumption by LDVs: x_4, x_5;
- production of renewables-based gas substituting NG: x_6, x_7, x_8;
- hydrogen and P2L in heavy-duty transport: x_9, x_{10};

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- hydrogen production and storage: x_{11}, x_{12}.

Table 6: Decision variables in the multi-objective optimisation.

Decision variable		Min	Max
x_1	PV capacity (MW)	19.7	200.0
x_2	Onshore wind capacity (MW)	9.7	68.5
x_3	Offshore wind capacity (MW)	0	3.6
x_4	LDV diesel consumption (TWh)	0	95.0
x_5	LDV gasoline consumption (TWh)	0	51.4
x_6	H_2 injected into the gas grid (TWh)	0	51.5
x_7	Synthetic gas from biomass hydrogenation (TWh)	0	219.2
x_8	Synthetic gas from biogas hydrogenation (TWh)	0	166.6
x_9	Synthetic liquid fuel from biomass hydrogenation (TWh)	0	134.6
x_{10}	Number of H_2 trucks	0	573475
x_{11}	Electrolyser power factor	1	10
x_{12}	H_2 storage capacity (days)	0	10

Therefore, the difference among the energy scenarios resulting from the optimisation analysis is due to a different mix of these decision variables, which are subject to a number of linear constraints arising from particular features of different energy sectors, as explained in the following.

Transport demand in vehicle-kilometres is assumed to remain constant in all energy scenarios for light-duty vehicles, D_{LDV}, at 32.13×10^{10} km; therefore, PEV electricity consumption, $C_{el,PEV}$, is estimated accordingly:

$$C_{el,PEV} = (D_{LDV} - x_4/\bar{c}_d - x_5/\bar{c}_g) \times \bar{c}_e \tag{3}$$

where $\bar{c}_d$, $\bar{c}_g$ and $\bar{c}_e$ indicate the average powertrain efficiency for diesel, gasoline and plug-in electric vehicles respectively, given in section 2.3.

Synthetic gas and liquid fuel production from gasified biomass can vary provided that the upper limit for biomass consumption, $C_{biomass,max}$, is not exceeded, according to the following linear constraint:

$$C_{biomass\rightarrow P2G} + C_{biomass\rightarrow P2L} \leq C_{biomass,max} \tag{4}$$

where $C_{biomass\rightarrow P2G}$ and $C_{biomass\rightarrow P2L}$ are the biomass input for gasification upstream processes to produce synthetic grid gas and liquid fuel respectively. These quantities can be evaluated according to the following equations, where parameters presented in section 2.4 (Tables 3 and 4) are used:

$$C_{gasified\ biomass\rightarrow P2G} = x_7/\eta_{biomass\rightarrow P2G} \times (1 - \%\mathrm{H2}_{biomass\rightarrow P2G}) \tag{5}$$

$$C_{biomass\rightarrow P2G} = C_{gasified\ biomass\rightarrow P2G} / \left[(1 - \sigma/\eta_{steam}) \times \eta_{cg}\right] \tag{6}$$

$$C_{gasified\ biomass\rightarrow P2L} = x_9/\eta_{biomass\rightarrow P2L} \times (1 - \%\mathrm{H2}_{biomass\rightarrow P2L}) \tag{7}$$

$$C_{biomass\rightarrow P2L} = C_{gasified\ biomass\rightarrow P2L} / \left[(1 - \sigma/\eta_{steam}) \times \eta_{cg}\right] \tag{8}$$

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with $C_{gasified\ biomass \rightarrow P2G}$ and $C_{gasified\ biomass \rightarrow P2L}$ representing the amount of gasified biomass to be hydrogenated for the production of synthetic grid gas and liquid fuel respectively.

The number of HDVs is assumed constant in all energy scenarios, so the number of diesel trucks is obtained as a difference:

$$n_{d,truck} = n_{Tot,truck} - x_{10} \tag{9}$$

The resulting annual energy consumption for hydrogen and diesel HDVs is therefore given by:

$$C_{\mathrm{H2},truck} = x_{10} \times \bar{c}_{\mathrm{H2},truck} \times km_{truck} \tag{10}$$
$$C_{d,truck} = n_{d,truck} \times \bar{c}_{d,truck} \times km_{truck} \tag{11}$$

The production of SLF is constrained to not exceed the consumption of diesel for heavy-duty transportation:

$$x_9 \leq C_{d,trucks} + C_{d,otherHDV} \tag{12}$$

where $C_{d,otherHDV}$ is equal to 39.5 TWh and is representative of diesel consumption in other areas of freight transportation.

The minimum electrolyser capacity $P_{ELT,\min}$ is obtained from the electrolyser efficiency and the overall hydrogen demand D_{H_2}, which in turn depends on the amount of hydrogen required by P2G and P2L processes and H_2 trucks:

$$C_{\mathrm{H2},biomass \rightarrow P2G} = x_7 \times \%\mathrm{H2}_{biomass \rightarrow P2G} / \eta_{biomass \rightarrow P2G} \tag{13}$$
$$C_{\mathrm{H2},biogas \rightarrow P2G} = x_8 \times \%\mathrm{H2}_{biogas \rightarrow P2G} / \eta_{biogas \rightarrow P2G} \tag{14}$$
$$C_{\mathrm{H2},biomass \rightarrow P2L} = x_9 \times \%\mathrm{H2}_{biomass \rightarrow P2L} / \eta_{biomass \rightarrow P2L} \tag{15}$$
$$D_{\mathrm{H}_2} = x_6 + C_{\mathrm{H2},biomass \rightarrow P2G} + C_{\mathrm{H2},biogas \rightarrow P2G} + C_{\mathrm{H2},biomass \rightarrow P2L} + C_{\mathrm{H2},truck} \tag{16}$$
$$P_{ELT,\min} = \frac{D_{\mathrm{H}_2}}{8784\,\mathrm{h} \times \eta_{ELT}} \tag{17}$$

The electrolyser power factor x_{11} then gives the actual electrolyser capacity P_{ELT} installed:

$$P_{ELT} = x_{11} \times P_{ELT,\min} \tag{18}$$

Finally, the hydrogen storage capacity S_{ELT} is evaluated based on the equivalent days of storage (x_{12}):

$$S_{ELT} = P_{ELT} \times 24\,\mathrm{h} \times x_{12} \tag{19}$$

3. Results and discussion

The concurrent objective functions to be minimised are CO_2 emissions and annualised total costs. In this regard, various possible optimal scenarios are found with a specific set of decision variables resulting in a Pareto front of optimum solutions, as shown in Figs. 2–4. Each of the three figures shows at the top the Pareto front and in the subsequent two graphs the impact of increasing renewable share, substituting the gas grid supply

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composition and the fleet supply, respectively. Data are reported in terms of variation with respect to 2017 base case scenario.

Renewable sources are kept close to the highest available capacity throughout the entire Pareto front, as shown in Fig. 2, with installations always above 95 % of the potential, due to the reduction in specific investment costs when IRES capacity increases (see Table 1). As a result, fossil fuel consumption in the power sector and related variable costs are strongly reduced; however, despite the complete phase-out of coal power plants assumed in all scenarios (see section 2.1), coal is not reduced by 100 % due to industry-sector consumption. As for renewables, slightly higher levels are selected for onshore wind power due to its lower seasonality with respect to PV, and to lower investment costs as compared to offshore turbines. As a matter of fact, offshore wind is generally cheaper than onshore one except form current Italian context where deep shore and landscape constraints are criticalities to overcome. Floating turbines and site selection at higher distances from the coast could play as game changer in that sector. However technology and policy, respectively, are still to be proven at National scale.

Regarding hydrogen pathways dedicated to synthetic gaseous fuels, Fig. 3 shows grid gas composition as well as electrolyser and storage capacity. The option of direct injection of hydrogen in the grid appears to be the least efficient option from a techno-economic optimisation perspective; indeed, hydrogen takes the smallest share of grid gas composition (1–2 %). This is certainly in line with the current percentage addition acceptance of the national infrastructures (0.5 %), which is the scope of this study: however, it is worth noting that the use at a lower spatial scale, such as a city or a district, could allow accommodating higher hydrogen fractions in terms of technology readiness and cost-efficiency due to a close production, distribution and use scheme [63]. SNG constitutes a share of the overall grid gas that varies in the range 6–13 %, either produced from biomass or biogas. As a result, NG can be reduced up to 74 % of the total composition. In the transition period, the role of NG is preferred as fossil fuel due to the lowest emissions, highest efficiency in combined cycles, widespread infrastructures, and long-term contracts to be respected. However, it is noteworthy that this is not the fuel of the decarbonisation scenario.

Among the different options to replace NG in the grid, the P2G pathways, where hydrogen is used for hydromethanation processes of gasified biomass or biogas, prove to be the most beneficial alternatives. In fact, with respect to injecting hydrogen into the grid in its pure form, when combined with gasified biomass or biogas, a lower amount of hydrogen is required to achieve an equivalent amount of CO_2 emissions reduction. In other terms, the same amount of hydrogen produced can generate a higher reduction in CO_2 emissions if injected into the gas grid in the form of SNG rather than in its pure form, thanks to what can be identified as a multiplication effect, as two renewable sources (in this case biomass or biogas and RES-derived hydrogen) are used instead of only one to replace NG.

SNG appears to be equally favourable when produced either from biomass or biogas: the former process shows a lower hydrogen share but higher costs, related to biomass supply, while the latter, despite higher hydrogen requirements and its lower efficiency, appears to be still suitable as biogas is supposed to be generated from zero-cost agricultural or zootechnical waste. It is worth mentioning that, even considering a cost for biogas feedstock in the range 4.5–5.9 EUR/GJ [58], the effect on total annual costs would be negligible, with an overall cost increase in the range 0.56–0.88 %. Furthermore, even

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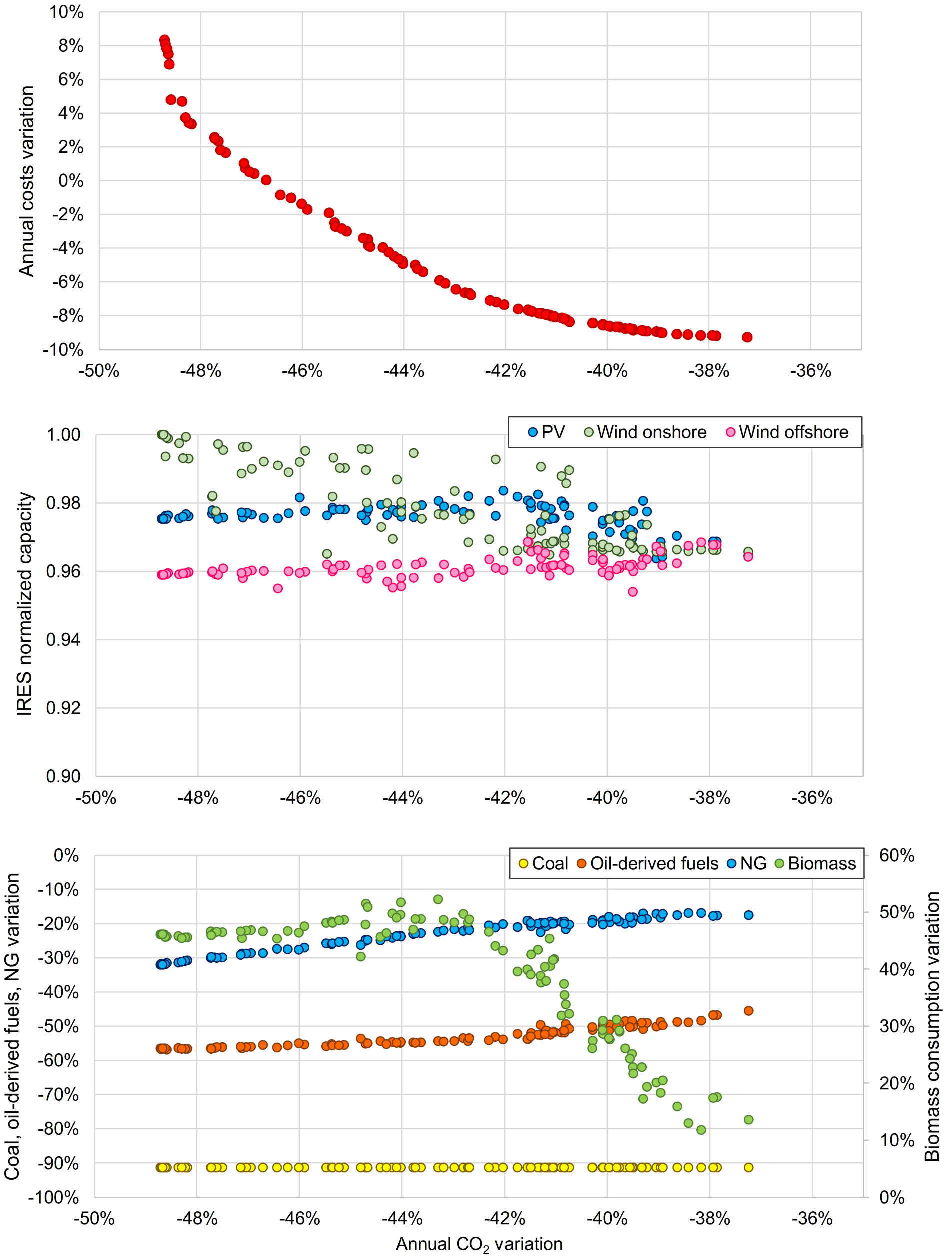

Figure 2: Annualised costs and CO_2 emissions in optimised energy scenarios (variation with respect to 2017): impact of IRES and changes in primary energy mix.

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Figure 3: Annualised costs and CO_2 emissions variation in optimised energy scenarios: impact of gaseous electrofuels, electrolyser power and hydrogen storage capacity.

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at the minimum level of CO_2 emissions reduction, synthetic gas fuels are higher than zero, meaning that scenarios implementing lower levels of these electrofuels would lead to the same or higher costs.

Electrolyser power is increased up to approximately eight times the average power required to fulfil the annual hydrogen demand. However, the variation of power oversizing factor (i.e. a factor that increases electrolysers power to accommodate IRES variation better) between 6 and 8 leads to a reduction in CO_2 emissions of only 1 percentage point at the price of an increase in annualised costs of 5 %. Showing the highest variation among the decision variables, both power oversizing factor and hydrogen storage capacity are the major causes of annual cost increase. However, despite large growth in storage capacity (mostly occurring from −42 % CO_2 emissions), the effect on the increase of final hydrogen products is very limited. On this matter, effects are expected from innovation in the electrolyser industry following the projected large-scale installations and establishment of already codified smart energy services that can provide different input data and subsequent optimisation results.

Fig. 4 shows the energy composition of both LDV and HDV sector. As for LDV, electricity ranges from 60–100 %, thus leading to a fleet purely made up of PEV. It is worth noting the higher beneficial effect in terms of CO_2 emissions of diesel over gasoline cars when PEVs are assumed to replace the conventional vehicle fleet. This is due to the higher efficiency of diesel cars compared to gasoline alternatives; however, this assessment might change if stricter regulations towards diesel vehicles are implemented.

With respect to synthetic liquid fuel (DME), its production increases linearly until reaching a plateau at 30–40 % of the overall fuel required by freight transport, while hydrogen takes the lion's share among HDV fuels with a plateau around 50 %.

Finally, it is worth observing that the Pareto front of optimal scenarios displays lower annual costs for almost three-quarters of the curve compared to the current situation. As shown in Fig. 5, this can be explained by the significant renewable penetration (fig. 2), which not only allows electrofuels to be favourably produced, leading to a reduction in fuel costs, but also makes it possible to support almost complete electrification of the private transport sector without resorting to conventional electricity generation. This is partly counterbalanced by the increase in investment costs that become significant at the end of the Pareto front, mostly due to the increase of electrolyser power and hydrogen storage. CO_2 costs are also included, which are set to 43 EUR/tCO_2 [39].

Another analysis is conducted to assess the impact of electrolysers efficiency on the pareto front in case other electrolysers of lower efficiency are adopted in the scenarios, given that the low operating flexibility of SOECs may not match the requirements of the available highly variable renewable power. The results are shown in Fig. 6. It can be observed that as the electrolysers efficiency diminishes so does the reduction of CO_2 emissions at a given cost level, as the excess of IRES production is not conveniently exploited. CO_2 emissions can be reduced by 43 % at most at 50 % electrolysers efficiency; any additional improvement in SOEC flexibility, through an increase of available electrolyser power, will not realistically lead to an improvement in CO_2 emission. Moreover, for a given value of CO_2 emission, overall annual costs can be reduced significantly when electrolyser efficiency is improved as a result of the reduction of variable (as in fuel) costs.

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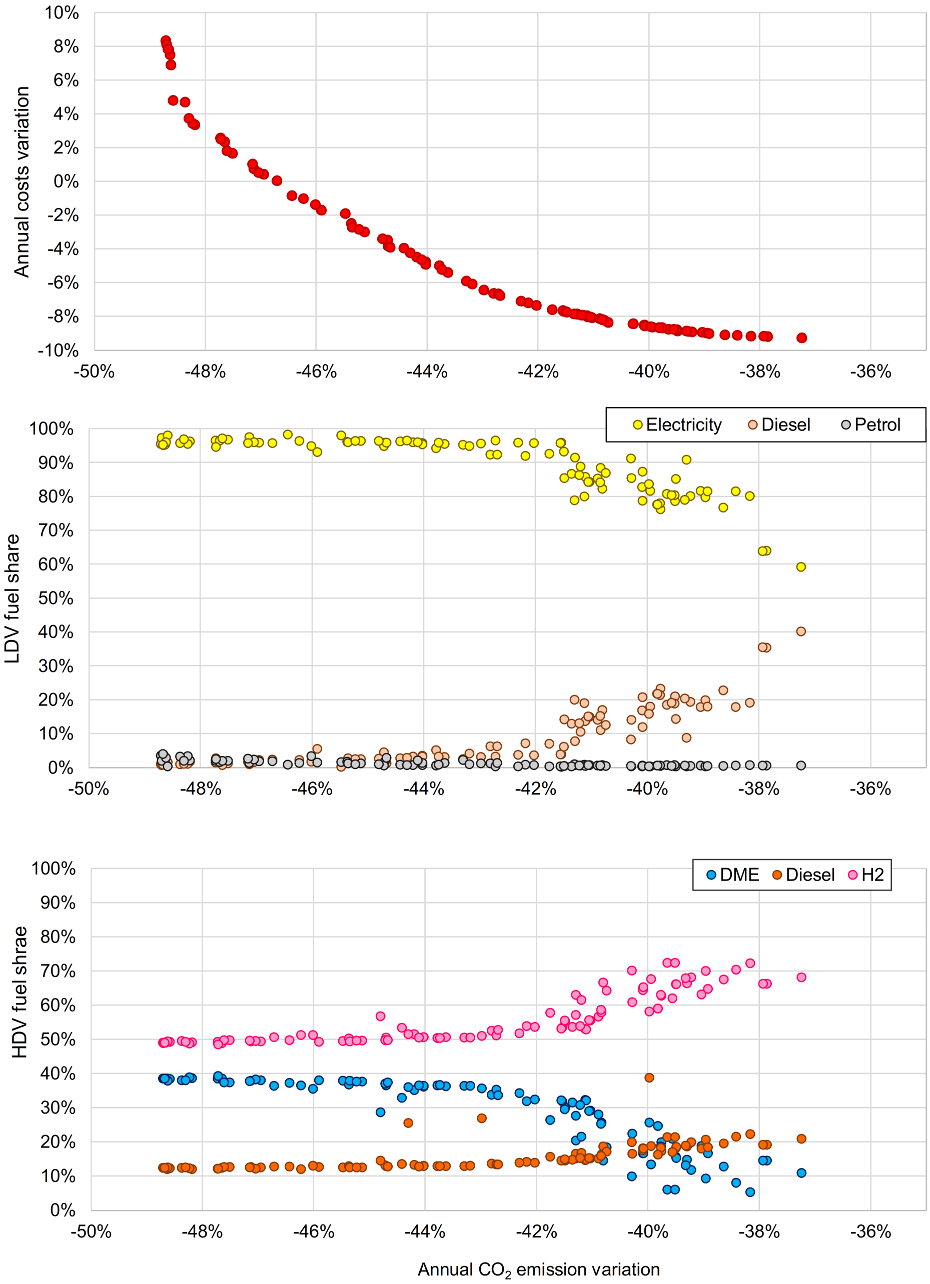

Figure 4: Annualised costs and CO_2 emissions in optimised energy scenarios (variation with respect to 2017): impact of LDV and HDV energy composition.

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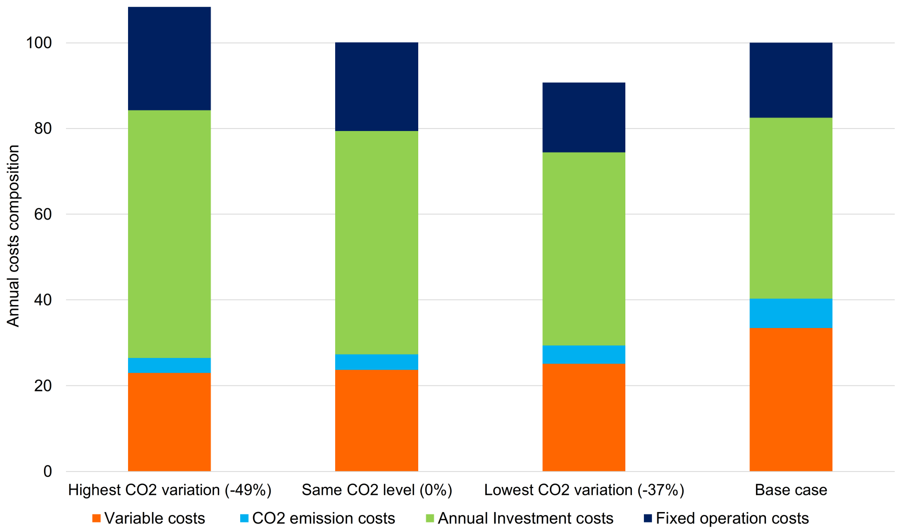

Figure 5: Annualised costs and CO_2 emissions in optimised energy scenarios (variation with respect to 2017): effect of FCEVs and P2L in heavy transportation.

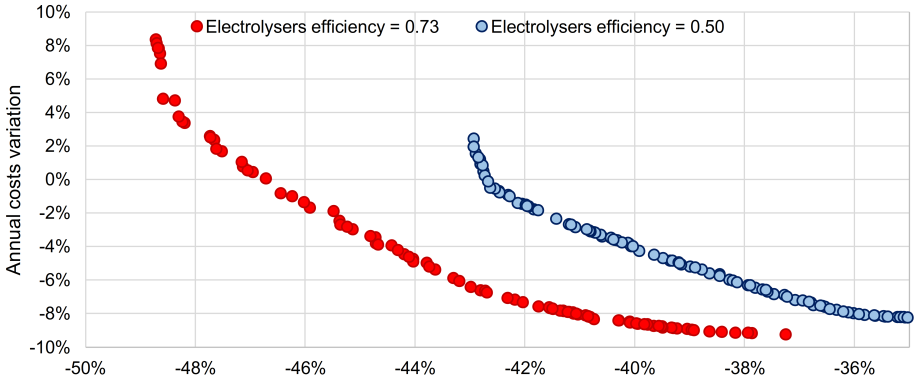

Figure 6: Annualised costs and CO_2 emissions in optimised energy scenarios: effect of electrolysers efficiency.

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4. Conclusions

This study proposes a variety of possible future scenarios for the Italian energy system that result from a techno-economic optimisation in which different sectors are involved and act in a synergic manner. A cost development curve is applied for the technologies involved assuming a reduction in their investment costs as their capacity increases.

The results show that the full utilisation of renewable power sources in electricity generation, the electrification of private transport, and the deployment of "green" hydrogen and electrofuels to partially replace both natural gas in the gas grid and diesel fuel in heavy transport lead to a reduction in CO_2 emissions of up to 49 % at the price of an increase in annual cost of 8 %. It is worth mentioning that the increase in annual costs is due to higher investment costs not fully compensated by the decrease in variable (mostly fuel) costs.

In particular, in the optimal scenarios IRES reach an installed capacity that is always above 95 % of their potentials, allowing a reduction in fossil fuel consumption mostly in the power sector. Due to the cost reduction with the increasing penetration, PEVs almost completely replace the conventional fleet in two-thirds of the optimal scenarios identified. SNG can replace 20 % of NG in the gas grid while, from the optimisation perspective, direct hydrogen injection gives a negligible contribution. On the other hand, hydrogen's role in powering FCEVs is quite significant: in the lowest emissions scenario, hydrogen accounts for 50 % of HDV fuel consumption and diesel can be reduced to 10 % of the total, with DME representing 40 % of heavy transport fuel.

It is worth noting that not all sectors of the Italian energy system are taken into account in this analysis. For example, heating and industry are not investigated. This suggests why full decarbonisation cannot be achieved with the assumptions underlining this study: it requires that all sectors in the national energy system are synergically interconnected so as to fully exploit the potential of renewable power sources.

Acronyms

BEV Battery Electric Vehicle

DME Dimethyl Ether

FCEV Fuel Cell Electric Vehicle

HDV Heavy-Duty Vehicle

ICEV Internal Combustion Engine Vehicle

IRES Intermittent Renewable Energy Sources

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LDV Light-Duty Vehicle

LR Learning Rate

MOEA Multi-Objective Evolutionary Algorithm

NG Natural Gas

P2G Power-to-Gas

P2L Power-to-Liquid

P2X Power-to-X

PEV Plug-in Electric Vehicle

PHEV Plug-in Hybrid Electric Vehicle

PV Photovoltaic

RES Renewable Energy Sources

SLF Synthetic Liquid Fuel

SNG Synthetic Natural Gas

SOEC Solid Oxide Electrolyser Cell

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