Modelling the integrated power and transport energy system: The role of power-to-gas and hydrogen in long-term scenarios for Italy

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This work analyses future energy scenarios at country scale, focusing on the interaction between power and transport sectors, where Power-to-Gas is expected to play a key role. A multi-node model is developed to represent the integrated energy system, including additional electrical load from plug-in electric vehicles, energy storage, and hydrogen production from excess electricity for fuel cell vehicles. Electricity supply-demand balance is solved hourly, while liquid and gaseous fuels for mobility are accounted for cumulatively over the year. The Italian system is investigated, considering different evo-lution scenarios up to 2030 and 2050. The simulations yield a maximum 57% share of renewable sources in the electricity mix in 2050, while biomass could account for a further 5%. Results show that the use of Power-to-Gas increases the overall share of renewable sources across the sectors. High coverage of hydrogen mobility demand by clean production (about 81%) is achieved in presence of a large installation of renewables and a substantial introduction of fuel cell vehicles. However, greenhouse gas emissions reduction does not attain the ambitious long-term targets. In the best scenario, transport approaches the 60% cut, while power sector achieves only half of the desired 95% variation, thus calling for additional measures.

Keywords: Power-to-Gas Hydrogen, Multi-node modelling, Long-term scenarios Integration, Power and transport

1. Introduction

In most countries, the energy system is undergoing profound modifications, mainly driven by the increasing concern about climate change. Besides the medium-term push on renewable energy sources (RES), greenhouse gas (GHG) emissions reduction, and energy efficiency measures with the 2020 and 2030 targets [1], the European Union (EU) is now committed to an 80% reduction of GHG emissions below 1990 level by 2050 [2]. This new objective is general, thus regarding all the sectors that involve consumption of energy in any form.

In recent years, a significant effort has been devoted to decarbonise power generation, with the installation of large capacity of RES-based power plants, especially wind and solar (from 80 GW in 2006 to 650 GW in 2016 cumulative installed capacity worldwide [3]). However, to meet the ambitious EU objectives, the transition must involve all the energy sectors. In particular, the second most relevant area in terms of carbon footprint is road transport, which accounted for about 27% of the final energy consumption [4] and 24% of GHG emissions [5] in Europe in 2015. Decarbonisation of transport requires a massive introduction of low- or zero-emission vehicles in replacement of conventional ones fed with fossil fuels, which are already encountering limitations in some countries (e.g., Norway and Netherlands). Plug-in electric vehicles[1] (PEVs) and hydrogen fuel cell electric vehicles[2] (FCEVs) both offer low or zero local pollution (NO_x, CO, particulate), but their impact on the overall system is different: PEVs increase the electrical load on the grid, hence requiring a further increase in low-CO_2 electricity generation, while FCEVs need clean hydrogen production pathways to be low-carbon solutions [6].

In this context, power generation and mobility are expected to interweave more and more, leading to a new structure of the

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[1] The category 'Plug-in Electric Vehicles' (PEVs) includes both Battery Electric Vehicles entirely run on electricity (BEVs) and Plug-in Hybrid Electric Vehicles featuring a fossil fuel-fed ICE coupled with an externally rechargeable battery (PHEVs).

[2] The option of plug-in fuel cell electric vehicles, which would add the possibility of externally charge the on-board battery, has also been conceived, but it is not considered in this work.

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overall multi-energy system. Energy storage will be crucial to help the integration of clean sources and applications. While batteries may be installed to manage intermittent electricity generation on short time scales, the Power-to-Gas (P2G) technology is receiving attention as a valid long-term storage option [7]. It recovers excess electrical energy from non-programmable RES and feeds it to electrolysis devices that produce carbon-neutral hydrogen.

The topic of decarbonisation is broadly present in literature. Regarding the power sector evolution, studies have investigated the effects of high penetration of renewable sources in terms of backup generation [8], storage needs [9], and costs variation [10]. Space and time averaging of the energy profiles have been studied, comparing storage introduction to grid extension [11] or analysing various options for grid improvement [12]. Analyses on electrical energy storage technologies have evaluated various available power system applications [13]. Lately, P2G use and integration have gained attention, and some works have estimated the installation potential for excess electricity recovery in future high-RES electricity systems, e.g. in Italy [14] and Spain [15]. About the interconnection of networks, studies have looked at the interaction between power and natural gas grids, e.g. analysing the natural gas grid operation when highly dynamic consumption profiles occur due to intermittent power generation [16]. In terms of sectors coupling, analyses on electricity and heat have mainly investigated smaller geographical scale, like city [17] or district [18]. Attention to the transformation of the transport sector appears to be a more recent research effort, with a focus on the interaction of new mobility solutions with the power grid [19] and the effect on GHG emissions [20]. The importance of the integration of power and transport sectors is growing, in particular due to the rising amount of electric and fuel cell vehicles available on the market [21].

This work investigates the role of P2G in an integrated multi-energy system. Looking at future scenarios characterized by a large installed capacity of intermittent RES plants, a significant amount of excess energy is expected, which could be properly exploited by P2G systems for the production of hydrogen [22]. It is straightforward to look at hydrogen-based mobility as a suitable application for the generated clean fuel. A model is proposed to represent the power generation and the road transport sectors, and simulate their combined behaviour, with the aim of assessing the hydrogen potential and estimating its relevance in coping with the EU emission targets. The model is applied to Italy, which is a member state of the EU and therefore subject to the above-mentioned objectives. Two alternative evolutions of the power sector and two forecasts on vehicles distribution are considered, generating four different scenarios. Due to the punctual availability of data, the transport sector is limited to passenger cars and light-duty vehicles. However, the procedure is general and the analysis could be extended to the whole transport sector.

First, the features of the proposed model are detailed. Then, the simulation of future scenarios of the Italian system is presented: data and assumptions are outlined before discussing the results in terms of energy sources shares. A comparison between the analysed scenarios studies the possibility of achieving the GHG emissions targets set by the EU. Large quantities of installed RES are essential for a proper exploitation of storage, while a high share of innovative mobility solutions is required to obtain a positive impact on the system.

2. Methods

To assess the role of the Power-to-Gas technology in supporting the penetration of RES, a model has been developed that integrates the different sections of the energy system. Analysing the interactions over time of the energy flows, the aim is to evaluate the achievable shares of renewable energy sources exploited in each sector and the combined effects on the overall system. Future scenarios, characterized by different values of installed RES capacity and stock of vehicles, are the focus of this work. They are either based on forecasted evolution by diverse research studies or specifically built according to estimates of maximum technical potential (i.e. without considering economic and political limitations).

The representation of the system is based on a lumped nodal scheme, meaning that no detailed positioning of plants and loads is taken into account within each node (i.e. infinite capacity grid) and only inter-nodal exchanges are subject to constraints. For both power and mobility sectors, the considered nodes depend on the geographical scale, on a case-by-case basis, as well as on actual limitations of the infrastructure (e.g., single connection). For analyses at country scale, the nodes can correspond to electrical market areas, where they exist, or to regional grouping.

The logical structure of the analysis is schematised by Fig. 1, and it is discussed in the next sections together with the assumptions required by the model. The main parameters for the types of storage systems considered are summarised in Table 1. Minimum number of equivalent working cycles for batteries and minimum equivalent operating hours (EOH) for P2G are defined according to techno-economic viability, as further detailed in Section 3.

Table 1
List of parameters for the energy storage systems considered.

Parameter	Value
PHS roundtrip efficiency	72 %
BESS roundtrip efficiency	90 %
BESS lifetime	3000 cycles
BESS minimum equivalent working cycles	200 cycles/y
P2G efficiency	65 %
P2G minimum equivalent operating hours	1500 h/y

2.1. Power sector modelling

In this work, wind, solar, geothermal, and hydroelectric power plants are classified strictly as renewables (label 'RES'), while biomass-based electricity generation is treated separately (label 'bioenergy') as it is programmable and not 100% carbon-neutral. Conventional generation includes fossil fuel-based power plants or import from adjacent countries (label 'conventional').

The model considers the requirement of constant balance between generation and load on the power grid at each time step (e.g., 1 h) over the considered time horizon (e.g., one year). The availability of excess electricity after RES generation is assessed and possibly exploited through large-scale storage systems: first, electric-to-electric solutions aimed at peak shaving and load shift

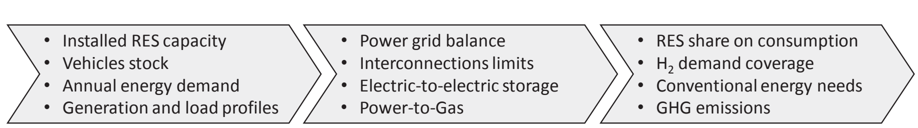

Fig. 1. Logical scheme of the developed method.

(like pumped-hydro and batteries); then, P2G for the production of carbon-neutral hydrogen. They are in competition, as the growth in the use of the formers reduces the excess energy available to the latter. Other technologies, focused on ancillary services to the grid, are out of the scope of this energy-based analysis.

The profile of electrical load is assumed equal to the historical one. The same assumption is made for the RES generation profiles, considering that the most effective locations have already been selected and the increase in capacity will be coherent. To do so, the absolute values in the reference year are linearly rescaled to the forecasted installed power of each technology under consideration in the analysed year, by keeping constant values of the equivalent operating hours. Similarly, the grid load profile is linearly rescaled to the future predicted yearly demand. Thus, it does not include electricity demand from PEVs, as the penetration is negligible (<0.1%) in past years; this contribution is estimated and added separately, according to each specific scenario.

Storage systems operation only involve intra-zonal energy exchange, imposing not to transfer electricity over long distances to store it. While pumped-hydro and batteries feature a two-way interaction with the power grid, P2G only accepts electrical energy from RES and it returns a gaseous fuel as product. In the first case, losses related to the charging/discharging processes are included, with state-of-the-art values (see Table 1); in the second, an efficiency equal to 65% is assumed, defined as the ratio between outlet hydrogen LHV-based energy content and inlet electricity (today's value for the P2G system composed of PEM electrolyser stack and balance of plant [23]).

The generation technologies available on the power grid are assumed to operate on the basis of a fixed dispatch priority order, schematised in Fig. 2 together with the energy flows internal to a single zone and the boundary considered for the energy balance.

The first priority level (Lev. I) corresponds to the use of renewables to cover the load as largely as possible. Waste-to-energy is also assigned the maximum priority together with RES, as the waste disposal through incinerators is considered a non-optional accomplishment to be guaranteed (a flat profile is considered). The residual load after level I is defined as:

$$RL^{I}_{z,t} = L_{z,t} - E_{sun,z,t} - E_{wind,z,t} - E_{geoth,z,t} - E_{hydro,z,t} - E_{WTE,z,t} \quad (1)$$

where z is the zone (node) considered, $L_{z,t}$ is the load in zone z at time step t and $E_{techn,z,t}$ is the energy generated by technology *techn* in zone z at time step t.

After level I, each zone features a positive or negative residual load, meaning that additional generation is needed or excess energy is available, respectively. In case of negative residual load, it has to be evaluated whether the energy accounted in $RL^{I}_{z,t}$ comes totally from RES and not from WTE; this is verified as long as the zonal generation from WTE is lower than the load in the same zone $L_{z,t}$.

The second priority level (Lev. II) involves the exchange of renewable energy between the macro-areas, using the available interconnections. A loss factor is applied to the energy flowing along transport lines and a minimization problem is solved to allow for the most effective electricity transfer: overall positive residual load is reduced as much as possible, given the availability of excess energy and the limits on power flowing along lines as constraints. As the minimization problem is linear, the Matlab® function *linprog* is used, exploiting the built-in dual simplex algorithm and imposing adequately small tolerances (in the Wh scale).

At the third priority level (Lev. III), electrical storage is exploited. Since more than one technology is taken into account, an inner priority order is defined. In this work, existing pumped-hydro plants and installation of batteries are considered, but the procedure can be extended to other ones. Pumped-hydro storage is the first to be 'filled in' due to its large capacity and zero self-discharge, while batteries are the first to be emptied due to the existence of a self-discharging loss.

At the fourth priority level (Lev. IV), a differentiation is introduced: a) if the node (macro-area) showcases excess energy, it is fed to electrolysers in Power-to-Gas plants; b) if residual load is still positive, bioenergy and conventional plants are used to fully cover the demand. Bioenergy is prioritised, as a low-emission option, up to its installed capacity; moreover, the compatibility with a given feedstock availability is checked. Finally, the term 'conventional generation' refers to any fossil fuel-based power generation option

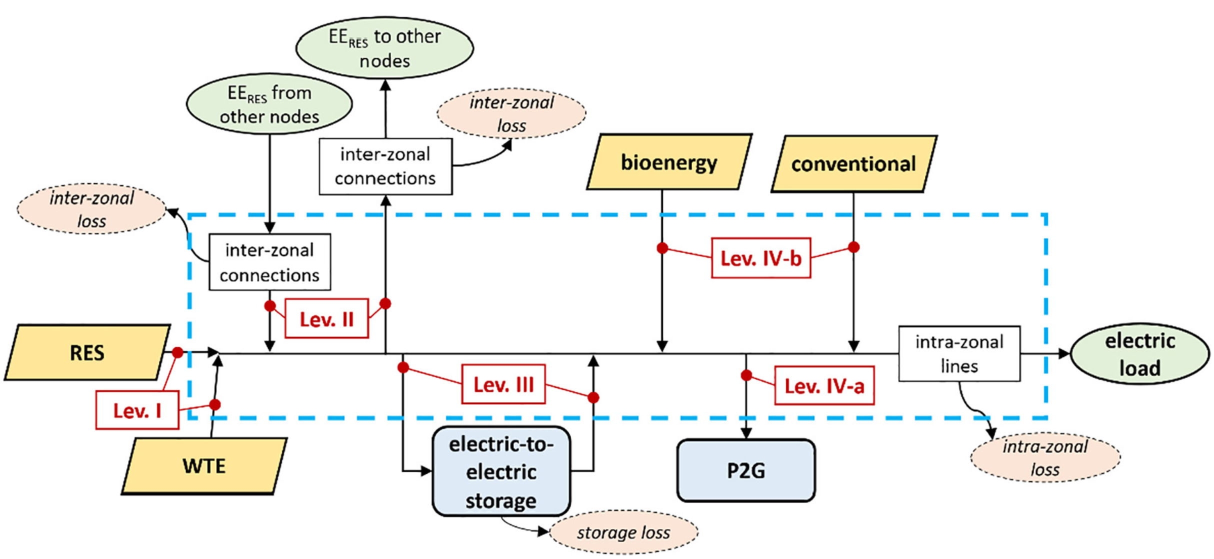

Fig. 2. Schematization of the macro-area with respect to electrical energy flows.

or electricity import from abroad and, as such, it is assumed to be always available to fulfil the energy balance.

At each level of the analysis, a residual load is defined, evidencing the contribution of each technology to the load.

2.2. Mobility sector modelling

The mobility section investigated in this work is the road transport. Today it is largely based on conventional vehicles, i.e. cars and trucks whose propulsion derives from fossil fuels burnt in an internal combustion engine (ICE). However, market evolution trends show that the share of PEVs is rapidly growing [24] and FCEVs have reached market maturity [25], so that they are present in any long-term study.

The total energy consumption for mobility involves a variety of fuels and vehicle types. Based on the stock of vehicles (from forecast on total number and shares), the specific consumption (assuming future average values equal to today BAT for innovative vehicles and to today average for ICE-based ones), and the travelled distance (as foreseen by research studies), the energy demand is evaluated for each fuel over the selected period using the same nodal resolution defined for the power grid.

The yearly electricity request from PEVs is shaped into a profile and added to the electrical grid load, thus affecting the power grid balance. The time step of the PEVs charging profile must be consistent with the power grid model one (in this work, a typical 1-day-long hourly profile is selected and identically repeated). Various studies are available to model the PEVs electrical demand profile, e.g. based on users' behaviour [26], cost-driven optimization [26], or RES availability [27]. Among the available literature profiles, a cost-driven one is selected [26], which shows two peaks, corresponding to the mid-day solar energy availability and to the night low electricity price (red line in Fig. 3).

A flat hydrogen demand from FCEVs is assumed, thanks to the possibility of long-term fuel storage and the short refuelling times. Alternatively, it could be shaped into an hourly profile if an additional analysis on limited storage capacity was performed. First, hydrogen is produced by electrolysis up to the availability of excess clean electricity, recovered accordingly to the installed capacity of P2G facilities, which is calculated for each node during the simulation to guarantee a minimum number of equivalent operating hours. The remaining hydrogen request is assumed to be covered by centralized steam methane reforming (SMR), as this is the most effective technology available today.

The consumption of fossil fuels by conventional vehicles can be accounted for in cumulative terms over the whole period analysed, since it does not interfere with the power grid dynamics. Biofuels presence, either in mixtures with fossil fuels (e.g., in fuel blends like E20 and E25) or consumed as pure fuels, is also considered. The availability of both fossil fuels and biofuels is considered a non-limiting aspect, since a large refinery capacity is available, and the delivered amount is expected to decrease over the long run due to the competition of PEVs and FCEVs.

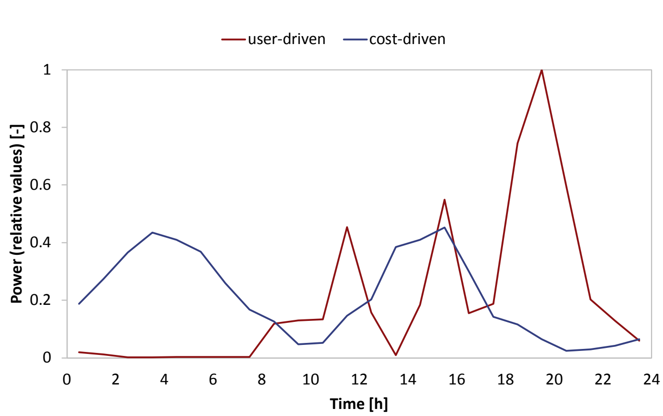

Fig. 3. Two PEVs charging profiles, given the same total daily demand (from Ref. [26], rescaled to unit peak power).

3. Italy: system description and data

The model is applied to Italy considering two long-term time horizons (2030 and 2050), to simulate and analyse the expected situation in terms of RES share and P2G role under different possible evolutions of the energy system.

The country is divided into six zones, corresponding to the electrical market zones as identified by the national TSO (see Fig. 4), mainly taking into account transport limitations along the high voltage lines. To limit the discussed scenarios, no variations are assumed for the power transmission limits, as these interventions are costly, slow, and often limited due to difficult social acceptance.

Attention is given to the introduction of storage. Besides the installation of P2G plants, the presence of two electric-to-electric technologies is considered: pumped hydroelectric storage plants and battery energy storage systems. P2G capacity is quantified, in each macro-area and for each scenario, on the base of the equivalent operating hours as explained above. Thanks to the Italian orography, pumped hydroelectric plants already feature a significant installed capacity (more than 7 GW nominal power and over 700 GWh storage capacity). Their distribution is uneven, with a massive presence in the 'NORD' macro-area (about 5 GW) which, however, does not showcase a large RES excess generation due to the presence of most of country's industries and electrical load. These capacities are assumed to stay constant along time, thus appearing unchanged in the scenarios. The installation of battery storage systems is calculated in each scenario to guarantee a minimum number of yearly equivalent cycles (defined as the ratio between the total input energy handled in a year and the available capacity). Based on the state of the art of the research [29], lithium-ion technology is selected as these devices appear to be the most promising ones. Given their lifetime in terms of equivalent charge-discharge cycles equal to 3000 cycles (mean value from literature [30]) and assuming a calendar lifetime of 15 years, an average of 200 equivalent cycles per year would be consistent with a proper use. The latter value is used as the minimum number of yearly equivalent cycles as defined above.

3.1. Power sector data

Geothermal and renewable hydroelectric installed capacity is assumed constant over the time, as no significant increase is foreseen due to resources limitation. Wind and solar PV capacity is considered to increase, as they are driving the RES transition, and load is expected to modify as well. Two power grid scenarios are taken into account:

- The first option is a forecast from ENTSO-E *Ten-Year Network Development Plan* [31]; among the four alternatives developed in the study, Vision 4 'European Green Revolution' is chosen, which has the highest increase both in renewable capacity and in load. Data are available up to 2030 only, and the 2050 scenario is built by extrapolation, assuming a linear trend from 2014.
- The second scenario is developed as a technical maximum in terms of installed capacity, coupled with the smallest load increase among the ENTSO-E options (0.26%/y from 2014, Vision 3). As said before, here 'technical' means that the figures depend on the combined resource availability, technological

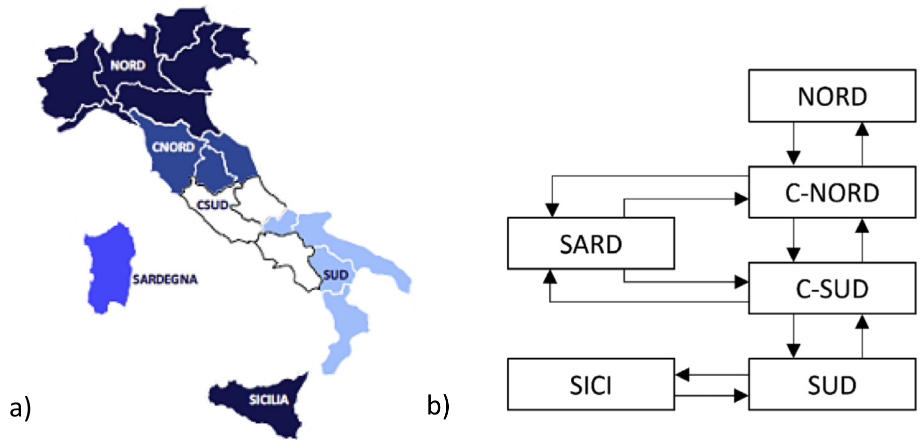

Fig. 4. Italian zonal division: a) geographical positioning [28]; b) modelling of the existing inter-zonal connections.

development, and environmental limitations (e.g., excluding natural parks and agricultural lands), without any political, economic, or logistic consideration. The wind potential in Italy is estimated in 49 GW based on [32], which considers only onshore turbines, due to the structure of the Italian coastline and the current BAT for offshore installations. The solar PV potential (110 GW) is evaluated from the available roofs and façades surface of buildings, taking into account the average irradiation (i.e. the value in central Italy, 1854.2 kWh/m^{2}y), a reference average module efficiency (19.7%), and an average system performance ratio (80%) [33]. The estimated technical potentials are assumed to be achieved in 2050, and the 2030 scenario is built by interpolation.

Since the ENTSO-E load data include the EVs consumption, the latter is first subtracted in order to have an estimate of the grid-only load. Subsequently, the electricity request from road transport is added coherently to the mobility scenario that is coupled to the power sector one (in total, four scenarios are generated for each future year).

The considered power sector scenarios are summarised in Table 2.

Intra-zonal losses equal to 4.3% are added to the net load, to account for medium- and low-voltage transmission and distribution losses [34].

As detailed in Section 2.1, both the generation of electricity from renewable energy plants and the electrical grid load in the scenarios are modelled with a profile analogous to the historical one. The use of historical profiles from 2013, 2014 or 2015 leads to variations in the residual load up to 10% in 2050 scenarios. The main contribution is due to hydroelectric generation, which is strongly affected by weather conditions. On the contrary, the role of storages (pumped hydro and batteries) appears stable: their contribution (i.e. the energy released to the system) shows only slight differences (they offer about 4 TWh/y and 1 TWh/y to help cover the residual load, respectively). In this work, 2015 is chosen as reference for the calculations, which makes the analysis conservative as it yields the smallest value of available energy to P2G, due to the low electricity generation from hydropower in that year.

Table 2
Power sector scenarios data of RES evolution and load growth for Italy (electrical load values do not include demand from mobility).

	Current situation	ENTSO-E (Vision 4)		Technical maximum[a]	
	2015	2030	2050	2030	2050
Solar PV [GW]	18.9	42.2	71.6	59.3	110.2
Wind [GW]	9.2	23.5	41.9	26.7	49.1
Geothermal [GW]	0.8	0.8	0.8	0.8	0.8
Renewable hydro [GW]	15.0	15.0	15.0	15.0	15.0
Electrical load [TWh/y]	297	319	370	296	312

[a] Maximum PV and wind installed capacities, minimum load growth (0.26%/y from 2014 [31]).

3.2. Mobility sector data

Road transport comprises passenger cars, light-duty vehicles, buses, and heavy-duty trucks. In this case study, the first two are investigated (also referred to as automobiles), which are already on track to a shift towards innovative technologies, while keeping the road-based use. On the contrary, the awaited change in the heavy-duty sector is likely to involve also a shift to other types of transport option for goods (e.g., railway), and bus development depends on the policy-regulated evolution of public transport. Today, the Italian automobiles sector is largely based on fossil fuels (over 99% of the fleet), with a non-negligible fraction of vehicles run on methane or LPG (8%) [35]. In terms of consumption, automobiles account for 65% of the total road transport [36], and yield a similar share on emissions.

Two forecasted scenarios about the evolution of vehicle types in the national stock are considered:

- The first one is proposed by IEA [37] and predicts a slight decrease in total number of automobiles with a large deployment of innovative mobility: in 2050, BEVs and FCEVs account for 45% of the total vehicles, while PHEVs cover a further 19%, reducing traditional ICE-based cars to 36%. The scenario refers to EU4 (France, Germany, Italy, UK) and is assumed valid for Italy.
- The second mobility scenario, which comes from a European Commission (EC) study [38], is less disruptive: in 2050, only 2% of the automobiles are run on hydrogen and BEVs are limited to 5% of the total, while conventional vehicles constitute 87% of the fleet. Moreover, the total number of vehicles increases by 12.7% from 2015 to 2050. This forecast is specific to Italy.

The complete sets of data referred to the whole country are gathered in Table 3.

Zonal data are obtained assuming that (i) the distribution of vehicles among the macro-areas (see Table 4) is constant over the long run, i.e. the percentage variation in the number of vehicles is

Table 3
Mobility sector scenarios data of fleet and specific consumption evolution for Italy.

	Specific consumption [kWh/km][a]		Share of vehicles				
			Today	EC forecast		IEA forecast	
	2030	2050	2015	2030	2050	2030	2050
ICE gasoline	0.52	0.52	49.71%	28.33%	14.56%	41.73%	9.63%
ICE diesel	0.75	0.75	41.96%	41.44%	25.45%	25.18%	6.67%
ICE LPG/methane	1.44	1.44	8.09%	15.73%	16.40%	4.32%	2.96%
HEV (gasoline)	0.50	0.50	0.22%	5.13%	15.53%	8.63%	13.33%
HEV (diesel)	0.58	0.58	0.01%	5.54%	15.14%	5.04%	2.96%
PHEV (gasoline)	0.44	0.36	0.01%	1.40%	3.89%	5.04%	11.85%
PHEV (diesel)	0.60	0.48		1.20%	2.43%	4.32%	7.41%
BEV	0.24	0.20		1.00%	4.86%	3.60%	14.81%
FCEV	0.29	0.25	0.00%	0.24%	1.74%	2.16%	30.37%
Total automobiles	–	–	37,332,037	39,198,639	42,058,273	37,066,980	35,999,283

[a] Energy units refer to electricity or fuel LHV, depending on the vehicle type.

Table 4
Zonal distribution of vehicles (actual data in 2015, assumed unchanged in 2030 and 2050) [35].

	NORD	CNOR	CSUD	SUD	SICI	SARD
Fraction of total fleet	46.0%	10.8%	21.2%	10.8%	8.5%	2.7%

equal across the country; (ii) the national shares about vehicle technologies apply homogeneously in each zone (as it is today [35]).

Average values of the specific consumption and of the yearly travelled distance are taken into account to properly evaluate the request of the various fuels. As mentioned in Section 2.2, specific consumption values for conventional automobiles are assumed constant over the long run, while BEVs and FCEVs efficiencies are assumed to improve, up to an average in 2050 equal to today BAT (see Table 3). As far as the yearly distances travelled by conventional automobiles is concerned, it is forecasted a decrease for gasoline vehicles (6900 km/y in 2030 and 6121 km/y in 2050) and an increase for diesel ones (14700 km/y in 2030 and 15616 km/y in 2050) [39]. PHEVs travelled distance is considered equal to the one of the ICE-based using the same fossil fuel, but it is allocated to fossil fuel and electricity with a 70–30 proportion in 2030 and with a 50-50 proportion in 2050. BEVs and FCEVs average travelling distance is assumed as the mean between gasoline and diesel ones.

In regards to biofuels, they are assumed to cover 10% of the fossil fuel demand in the future; this is coherent with the mixing possibilities and equal to the limit set by EU in the 2020 energy goals [40] (no new targets have been set for the following years, and the topic is debated).

Since the refuelling procedure for FCEVs is similar to that of methane cars and not significantly different from gasoline or diesel, no detailed storage analysis is performed, i.e. storage is considered sufficient to buffer production and demand at all time and no refuelling profile is defined.

4. Scenarios results and discussion

Given the system topology, its main parameters, and the reference data (i.e. power generation capacity, electrical profiles, and automobiles fleet in 2015), simulations are performed for each scenario and for each analysed year. In each run, first the scenario is selected and set up (import of data, hourly profiling of electrical load and fuels consumption), then the sequential procedure for the power grid simulation (Levels I-IV) takes place, including the determination of the installed capacity of P2G and batteries, which is based on a sensitivity analysis. Finally, having computed the availability of excess energy, the production of clean hydrogen is evaluated and compared with the demand. The last step is the calculation of the shares of each source, both in the power sector alone and in terms of primary energy required by the overall system.

The first aspect analysed is the share of sources in the power generation, which is interweaved with mobility as PEVs influence the electric load. Contribution from storage (pumped-hydro and batteries) is separated from the other sources in order to quantify their role, but it corresponds entirely to renewable energy. In 2030, RES share (including storage) is in the range 37–46%. In 2050, it reaches 57% at most. Results for 2050 are shown in Fig. 5 (a similar behaviour is found in 2030).

Comparing the scenarios, the discriminating factor is the installed RES power generation capacity, while different mobility options scarcely affect the results, coherently with the fact that the observed quantities refer to the electrical energy only and the PEVs contribution to the total electric load is rather small (below 6%). A different situation appears when looking at the primary energy shares of the combined power and transport system (see below). As expected, electricity generation has higher RES shares when the 'Technical maximum' scenario is introduced for the power sector, thanks to the larger installed capacity. Given this, a mobility scenario shifted towards conventional vehicles (label 'EC') yields 1 percentage point advantage in terms of electrical RES share since it includes less PEVs and thus a lower additional load.

The contribute of electric-to-electric storage is generally small, despite the large installed capacity involved (see Table 5). This is partially due to the constraint of intra-zonal use, which does not allow to exploit large RES excess energy in southern zones to feed pumped-hydro storage installed in northern zones and later cover the residual load. However, interconnections among zones are already heavily exploited and little room is left for additional energy flows.

For the purposes of the analysis, one of the most interesting results is the availability of excess energy that can be used in P2G plants, to be compared with the actually used amount. The latter depends on the installed capacity, which is based on the equivalent operating hours achievable (see Section 2), i.e. on the occurrence and size of the peaks. Table 6 presents the values, summarised at country scale after the calculation is performed separately for each zone. The total installed P2G capacity lies between 26 and 28 GW under the power sector 'Technical max' scenario, corresponding to about half of the maximum peak power of excess RES generation (52–54 GW). In the ENTSO-E forecast, peaks are smaller (around

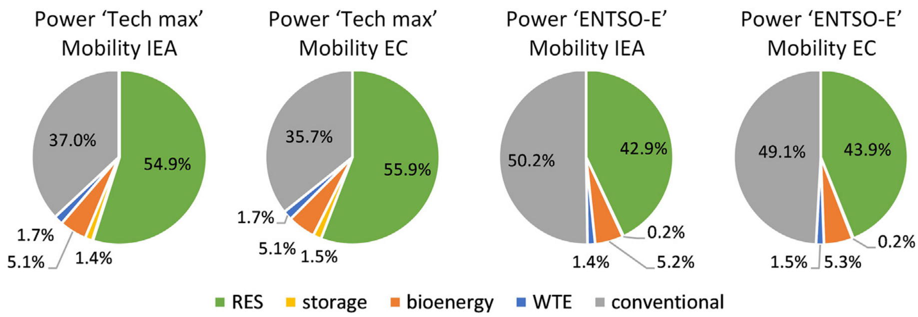

Fig. 5. Shares of sources in electricity generation in Italy in 2050, by scenario.

Table 5
PEVs role, battery storage installation, and output of electric-to-electric storage in Italy in 2050, by scenario.

		Power sector 'Tech max'		Power sector 'ENTSO-E'	
		Mobility IEA	Mobility EC	Mobility IEA	Mobility EC
Ratio of PEVs demand to total electricity demand	%	6.2%	2.3%	5.0%	2.0%
Total energy output by PHS	TWh/y	3.49	3.80	0.57	0.67
Installed BESS capacity	GWh	9.3	9.9	1.3	1.4
Total energy output by BESS	TWh/y	1.33	1.41	0.14	0.15

Table 6
P2G installed capacity and hydrogen production compared with demand in Italy in 2050, by scenario.

		Power sector 'Tech max'		Power sector 'ENTSO-E'	
		Mobility IEA	Mobility EC	Mobility IEA	Mobility EC
Available excess energy	TWh_{el}	46.0	49.2	13.1	14.6
Highest peak of excess energy	GW	51.8	53.6	22.7	24.4
Installed P2G capacity	GW	26.2	27.7	4.9	6.1
Recovered excess energy	TWh_{el}	39.4	41.7	7.4	9.2
H_2 production by P2G	kt/y	735.5	777.6	138.1	171.9
H_2 request by mobility	kt/y	903.1	60.5	903.1	60.5
P2G coverage of H_2 request	%	81.4%	100.0%	15.3%	100.0%

23 GW) and installed P2G capacity covers a smaller fraction of the maximum peak (5–6 GW, depending on the mobility scenario). The coverage of the hydrogen demand in the transport sector is calculated at country scale assuming that, once produced in a zone, the clean hydrogen can be transported to other macro-areas without problems. This is particularly important as, for example, northern zones (NORD, CNORD) have a significant request but no installed P2G capacity (see Table 7). Fuel transport across the country appears to be economically feasible as, in the long term, its cost differs only by about 5% from that of liquid fuels: the cost to move for 100 km on a truck the fuel needed to propel an automobile for 100 km is 8.33 c€ for hydrogen against 7.89 c€ for diesel (calculations based on recent statistics on fuel consumption [39] and travelled distance [41] for freight transport). It means that, even if the tank/payload mass ratio for hydrogen is higher than that for diesel, the lower specific consumption of FCEVs (in terms of kWh_{fuel}/km) plays an important role.

In the 2030 scenarios, even at high RES capacity and low PEVs load, the excess electrical energy is low and its profile combined with the requirement of 1500 EOH yields zero or close-to-zero installation of P2G facilities. Thanks to the strong increase in RES capacity and the small number of innovative vehicles, the scenario featuring 'Technical maximum' power sector and 'EC' mobility has 6.9 TWh/y excess clean electricity, and a 0.8 GW installed capacity of electrolysers is capable to satisfy the hydrogen request and the EOH requirement. However, the RES share in electricity consumption does not exceed 45.8%. Combining the 'Technical maximum' power sector with a shift to innovative vehicles (IEA mobility scenario), estimated P2G installed capacity is 0.5 GW, covering less than 20% of the hydrogen request by FCEVs. In the cases that consider the ENTSO-E scenario for the power sector, no P2G plant is introduced.

Focusing on 2050, more interesting figures are achieved; the results are shown in Table 6. It is evident that a low amount of

Table 7
Installed P2G capacity and hydrogen production by zone in 2050, for the scenario "Power sector 'Tech max' - Mobility IEA".

		NORD	*C-NORD*	*C-SUD*	*SUD*	*SICI*	*SARD*	*Italy*
Available excess energy	TWh_{el}	1.28	2.14	1.92	31.01	6.87	2.82	46.04
Installed P2G capacity	GW	0.0	0.0	0.0	20.5	4.3	1.4	26.2
Hydrogen production	kt/y	0.0	0.0	0.0	575.5	120.6	39.4	735.5
Hydrogen request	kt/y	415.7	97.2	191.1	97.9	76.7	24.5	903.1

excess energy (power sector ENTSO-E scenario) already leads to a non-negligible hydrogen production. However, it is sufficient to cover the whole demand from mobility only if this sector comprises a limited number of FCEVs (mobility EC). When their number grows (mobility IEA), a large excess energy is needed to produce the required hydrogen through clean electrolysis. Indeed, only the 'Technical maximum' power sector scenario gets close to 100% coverage of the hydrogen request. In general, a large installation of renewables is needed to achieve strong results in terms of alternative fuels production. Complete recovery of the excess electricity is not obtained in any scenario, due to the imposed feasibility requirement for P2G. Considering the scenario based on mobility IEA and power sector 'Technical max', no 100% coverage of the demand would be achieved even if the EOH requirement was cancelled, allowing to deploy electrolysers operating for very short total periods to catch all available RES excess energy: the max hydrogen production, using the whole available excess electricity, is 858.4 kt/y, which would be sufficient to power about 95% of FCEVs estimated fleet.

For the scenario "Power sector 'Technical max' - Mobility IEA", Table 7 presents the results detailed by geographical zone according to the division of Fig. 3. The uneven distribution of loads and supplies is visible: large electrical loads in northern areas lead to very limited excess energy (related to rare generation peaks, unable to guarantee the installation of P2G devices), while large solar and wind potential in southern regions allows for high installed capacities and subsequent large availability of excess energy. Due to the characteristics of the Italian energy system, inter-zonal power transport limits play an important role, while the feasibility of hydrogen transport discussed in the calculations above offers an interesting solution to integrate large RES capacity in the power grid.

Finally, the study analyses the share of RES in the overall system, made up of electricity given to the grid when produced, additional postponed feeding thanks to storage, and clean fuels introduction in the transport sector. The calculation considers the primary energy values as this allows to adequately sum and compare different types of energy flows and fuels. Thus, the RES-based pathways can be highlighted and the combined effects on the two subsystems can be observed. The evolution of both sectors affects the results. Given a power sector option, Mobility EC always leads to lower RES shares; this is in line with the limited introduction of alternative vehicles so that, even if the hydrogen ones are entirely fed with a clean fuel and the PEVs are largely supplied by renewable electricity, the presence of abundant traditional ICE-based vehicles yields high primary energy consumption values. Once again, the most positive situation corresponds to IEA mobility and 'Technical maximum' power sector scenario. However, RES share is still below 40%, approaching 50% if considering also WTE and biomass. Complete results are shown in Fig. 6.

5. Greenhouse gas emissions analysis

The energy system transition aims primarily at reducing the GHG emissions into the atmosphere, to hinder climate change. The shift is driven by a massive addition of RES capacity, storage technologies, and other low-carbon solutions. The introduction of innovative vehicles gives also advantages on local pollution, as BEVs, PHEVs, and FCEVs have low or zero emissions of NOx and particulate, with relevant impact at city scale. Since the focus of this work is on system scale performance, the attention is given to GHG emissions as they are responsible for global effects. In this section, they are evaluated for the scenarios previously described and simulated. First, the four combinations of future power and transport sectors are juxtaposed to understand which actions are more effective. Then, a comparison with the EU targets is performed.

Emissions related to each technology and source are accounted for using the well-to-tank and well-to-wheels coefficients accurately calculated by JEC [42], which are given in terms of equivalent CO_2. Hydrogen demand in excess of the P2G production is assumed to be covered by SMR production fed with natural gas from the grid. For simplicity, the whole portion of electricity generation defined as 'conventional' is considered to come from a natural gas combined cycle, which is the most common type of plant in Italy and the most efficient fossil fuel-based option available.

In Fig. 7, the yearly emissions of equivalent CO_2 in 2050 are represented, together with the situation in 2015 as reference. While any of the considered scenario leads to a reduction, the importance of transport sector is clear: the two lowest GHG-emitting scenarios are based on the mobility forecast that pushes the introduction of innovative vehicles (Mobility IEA), as it drastically reduces the use of fossil fuels. However, a large installation of RES plants is important as well, since it allows to generate the new energy

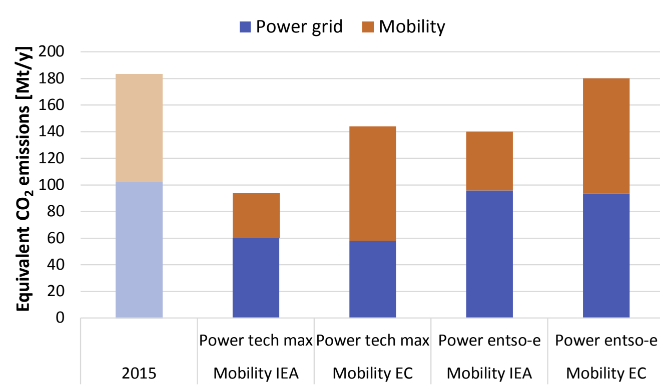

Fig. 7. Equivalent CO_2 emissions in 2050, by scenario, compared to the situation in 2015.

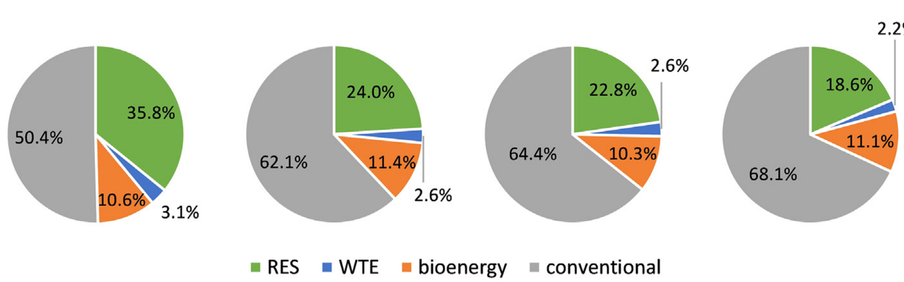

Fig. 6. Primary energy shares in Italy in 2050, by scenario.

Table 8
Emissions variation by scenario, compared to the target reduction from the European Union.

		EU target	Power sector 'Tech max'		Power sector 'ENTSO-E'	
			Mobility IEA	Mobility EC	Mobility IEA	Mobility EC
2015−2030	Power	−37.4 to −56.5%	−30.0%	−30.8%	−11.3%	−12.2%
	Transport	+5.1 to −20.3%	−18.6%	+11.6%	−18.0%	+11.9%
2015−2050	Power	−90.5 to −98.6%	−41.1%	−45.5%	−6.2%	−8.1%
	Transport	−59.7 to −71.1%	−58.6%	+5.6%	−45.5%	+6.2%

vectors for mobility (i.e. electricity and hydrogen) on a higher share of clean pathways, further reducing the carbon footprint of the vehicles.

To analyse the success or failure in reaching the EU long-term objectives (which are detailed by sector in Ref. [2]), a further control is needed, as the targets are stated with reference to 1990 levels. Since historical data on GHG emissions are available from different datasets, in order to have comparable values, a two-step procedure is applied. First, the variation occurred from 1990 to 2015 is calculated from a dataset [43], and the further reduction to be achieved from 2015 to the future year (2030 or 2050) is evaluated for each sector (column 'EU targets' in Table 8). Then, the variation between 2015 and the future year is computed using the results of the performed simulations. Results are shown in Table 8. When innovative solutions are largely introduced, the mobility sector appears to achieve the goals; on the contrary, the power generation is capable to achieve strong reductions of GHG emissions but, since it is required a huge effort in the decarbonisation route, it does not seem perfectly on track to the ambitious objectives set by the European Union in the latest energy plans [2]. If the proposed 'Technical maximum' is really an upper bound for wind and PV plants, other technologies may be needed, including other renewables, CO_2 sequestration, actions towards energy saving and efficiency improvements, etc.

6. Conclusions

A model has been developed for the simulation of the long-term evolution of integrated power and transport sections of the energy system at regional or national scale. Indeed, the two sectors are interweaving more and more as the deployment of large fleets of PEVs changes the electric load amount and profile, and FCEVs introduce a hydrogen demand that could be satisfied by the Power-to-Gas technology. The model is based on the power grid structure (topology definition and balance requirement) and takes also into account the demand of the various fuels by road transport. It allows to consider multiple types of storage as part of the system, either power-to-power or power-to-gas. In particular, P2G has been considered in this work to recover excess electricity from RES and produce clean hydrogen. As case study, different evolution scenarios of the Italian energy system have been investigated and compared from a technical and environmental point of view. Results show that, when large RES power generation capacity is installed, the coupling with the transport sector is fruitful and significant amounts of clean fuels can be produced to foster decarbonisation. On the contrary, in some scenarios the renewable energy availability is not sufficient to cover the foreseen demand in both mobility and electricity sectors, even in presence of energy storage. A strong increase of RES capacity is consequently mandatory also to help the mobility sector. The most attractive situation is found when the maximum technical potential of RES installation is deployed together with an aggressive evolution of the mobility towards PEVs and FCEVs. In this scenario (labelled "Power sector 'Tech max' - Mobility IEA") approximatively 81% of the hydrogen mobility demand and 57% of the electrical load are covered by renewables, while the overall share of RES and bioenergy in the primary energy consumption adds up to 47%. However, the EU targets on GHG emissions are rather challenging and even the most ambitious forecasts about RES installation and innovative mobility introduction do not guarantee that the objectives will be fully accomplished, especially in the power sector, evidencing the need for other technologies as well as strong energy efficiency actions to reduce the energy demand.

List of acronyms

BAT	Best Available Technology
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
CO2	Carbon Dioxide
EC	European Commission
EOH	Equivalent Operating Hours
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse gas
H_2	Hydrogen
ICE	Internal Combustion Engine
IEA	International Energy Agency
LPG	Liquified Petroleum Gas
PEV	Plug-in Electric Vehicle (either BEV or PHEV)
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydro Storage
PV	Photovoltaic
P2G	Power-to-Gas
RES	Renewable Energy Source
RL	Residual Load
WTE	Waste-To-Energy

References

[1] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 for the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union 2009;140:16−62.
[2] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A roadmap for moving to a competitive low carbon economy in 2050. 2011.
[3] IRENA. Renewable capacity statistics. 2016. p. 2016.
[4] Eurostat. Energy balance sheets - 2015 data - 2017 edition. 2017. http://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-EN-17-001 (accessed November 28, 2017).
[5] European Environment Agency. Annual European Union greenhouse gas inventory 1990-2015 and inventory report 2017. 2017. https://www.eea.europa.eu//publications/european-union-greenhouse-gas-inventory-2017.
[6] Ruth M, Laffen M, Timbario TA. Hydrogen pathways: cost, well-to-wheels energy use, and emissions for the current technology status of seven hydrogen production, delivery, and distribution scenarios. 2009. NREL Technical Report.
[7] Lehner M, Tichler R, Steinmueller H, Koppe M. Power-to-Gas: technology and business models. Springer; 2014.
[8] Gils HC, Scholz Y, Pregger T, de Tena DL, Heide D. Integrated modelling of variable renewable energy-based power supply in Europe. Energy 2017;123:173−88. https://doi.org/10.1016/j.energy.2017.01.115.

[9] Doyle JR, Johlas H. Energy storage considerations for high renewable power penetration: a case study. In: SenGupta S, Zobaa AF, Sherpa KS, Bhoi AK, editors. Advances in smart grid and renewable energy. Springer, 2018. https://doi.org/10.1007/978-981-10-4286-7_40.
[10] Lu B, Blakers A, Stocks M. 90—100% renewable electricity for the south west interconnected system of western Australia. Energy 2017;122:663—74. https://doi.org/10.1016/j.energy.2017.01.077.
[11] Steinke F, Wolfrum P, Hoffmann C. Grid vs. storage in a 100% renewable Europe. Renew Energy 2013;50:826—32. https://doi.org/10.1016/j.renene.2012.07.044.
[12] GridTech, Deliverable D4.2: analysis and discussion of the results of the four pan-European scenarios on the implementation of new innovative technologies fostering RES-Electricity and storage integration.
[13] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511—36. https://doi.org/10.1016/j.apenergy.2014.09.081.
[14] Guandalini G, Robinius M, Grube T, Campanari S, Stolten D. Long-term power-to-gas potential from wind and solar power: a country analysis for Italy. Int J Hydrogen Energy 2017;42:1—18. https://doi.org/10.1016/j.ijhydene.2017.03.081.
[15] Bailera M, Lisbona P. Energy storage in Spain: forecasting electricity excess and assessment of Power-to-Gas potential up to 2050. Energy 2018;143: 900—10. https://doi.org/10.1016/j.energy.2017.11.069.
[16] Chertkov M, Backhaus S, Lebedev V. Cascading of fluctuations in interdependent energy infrastructures: gas-grid coupling. Appl Energy 2015;160: 541—51. https://doi.org/10.1016/j.apenergy.2015.09.085.
[17] Nastasi B, Lo Basso G. Power-to-Gas integration in the transition towards future urban energy systems. Int J Hydrogen Energy 2017;42:23933—51. https://doi.org/10.1016/J.IJHYDENE.2017.07.149.
[18] Girardin L, Maréchal F, Dubuis M, Calame-Darbellay N, Favrat D. EnerGis: a geographical information based system for the evaluation of integrated energy conversion systems in urban areas. Energy 2010;35:830—40. https://doi.org/10.1016/j.energy.2009.08.018.
[19] Tarroja B, Shaffer B, Samuelsen S. The importance of grid integration for achievable greenhouse gas emissions reductions from alternative vehicle technologies. Energy 2015;87:504—19. https://doi.org/10.1016/j.energy.2015.05.012.
[20] Sohnen J, Fan Y, Ogden J, Yang C. A network-based dispatch model for evaluating the spatial and temporal effects of plug-in electric vehicle charging on GHG emissions. Transport Res Transport Environ 2015;38:80—93. https://doi.org/10.1016/j.trd.2015.04.014.
[21] Robinius M, Otto A, Heuser P, Welder L, Syranidis K, Ryberg DS, Grube T, Markewitz P, Peters R, Stolten D. Linking the power and transport sectors - Part 1: the principle of sector coupling. Energies 2017;10:956. https://doi.org/10.3390/en10070956.
[22] Schiebahn S, Grube T, Robinius M, Tietze V, Kumar B, Stolten D. Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. Int J Hydrogen Energy 2015;40:4285—94. https://doi.org/10.1016/j.ijhydene.2015.01.123.
[23] Fuel Cells and Hydrogen Joint Undertaking. Development of Water Electrolysis in the European Union; 2014.
[24] McKinsey. EVolution. Electric vehicles in Europe: gearing up for a new phase?. 2014.
[25] Samuelsen S. The automotive future belongs to fuel cells. IEEE Spectrum 2017;54(2):38—43.
[26] DEFINE. DEFINE synthesis report. 2015.
[27] IEA (International Energy Agency). Technology Roadmap - Solar Photovoltaic Energy. 2014.
[28] Terna, Sistema Elettrico, http://www.terna.it/it-it/sistemaelettrico.aspx (accessed April 4, 2017).
[29] IRENA. Battery storage for renewables: market status and technology outlook. 2015.
[30] European Association for Storage of Energy (EASE), Energy storage technologies, http://ease-storage.eu/energy-storage/technologies/ (accessed May 10, 2017).
[31] ENTSO-E. Ten-year network development plan 2016 - Scenario development report. 2015.
[32] Hoefnagels R, Junginger M, Resch G, Panzer C, Held A. Re-shaping project - long term potentials and costs of RES - Part I: potentials. Diffusion and Technological learning; 2011.
[33] Defaix PR, van Sark WGJHM, Worrell E, de Visser E. Technical potential for photovoltaics on buildings in the EU-27. Sol Energy 2012;86:2644—53. https://doi.org/10.1016/j.solener.2012.06.007.
[34] Autorità per l'Energia Elettrica il Gas e il Sistema Idrico. Deliberazione 23 luglio 2015 n. 377/2015/R/eel. Revisione dei fattori percentuali convenzionali di perdita e del meccanismo di perequazione delle perdite sulle reti di distribuzione di energia elettrica. 2015.
[35] Automobile Club d'Italia (ACI), Annuario statistico 2016, http://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/annuario-statistico/annuario-statistico-2016.html (accessed January 17, 2017).
[36] Ministero dello Sviluppo Economico, Statistiche dell'Energia, http://dgsaie.mise.gov.it/dgerm/ (accessed January 17, 2017).
[37] IEA (International Energy Agency). Technology Roadmap - Hydrogen and Fuel Cells. 2015.
[38] European Commission. EU Reference Scenario 2016. Energy, transport and GHG emissions: Trends to 2050. 2016.
[39] Unione petrolifera. Previsioni di domanda energetica e petrolifera italiana 2016-2030. 2016.
[40] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport. Official Journal of the European Union 2003;123:42—6.
[41] Eurostat, Freight transport statistics, http://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics (accessed February 13, 2017).
[42] JEC - Joint Research Centre-EUCAR-CONCAWE collaboration. Well-to-Wheels Report version 4.a. 2014.
[43] Istituto Superiore per la Protezione e la Ricerca Ambientale, Historical series of greenhouse gases emissions 1990-2015 (tables available from the website), http://www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni (accessed January 26, 2017).