Long-term power-to-gas potential from wind and solar power: A country analysis for Italy

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Challenges related to variability of renewable energy sources (RES) recently arose in many countries and several solutions based on energy storage were proposed; among them, a promising option is Power-to-Gas (P2G), able to recover excess and unbalanced electrical energy. In this work, an assessment of long-term P2G potential is performed on a country scale, based on the analysis of electrical system historical data series, rescaled in order to consider the evolution of load and installed wind and solar capacity. In a long-term perspective, it is assumed the complete exploitation of the technical potential of the RES, which represents an upper deployment boundary with current technology. Once satisfied the electric load, residual energy to the P2G system and hydrogen production are calculated on a hourly basis; P2G installed capacity is a consequence of the assumed target on minimum operation on a yearly basis. The Italian case is analyzed, evidencing that the recovered excess energy from RES could substitute nearly 5% of current natural gas con-sumption or about 7% of national fuel consumption when used for hydrogen mobility. A range of options and a sensitivity analysis on assumptions is presented, showing scenarios with up to 200 GW of installed RES and a 50% additional load with respect to current one. In addition, the extension of the model to a zonal grid structure evidences the impact of transmission lines saturation that may increase gas production up to 50%. Results are compared with the German case, considered in a previous work, evidencing differences due to the diverse energy production mix.

Keywords: P2G, Power-to-Gas Hydrogen production Italian scenario, Energy mix, Residual energy

Introduction

Renewable energy share is continuously increasing in most industrialized countries, allowing environmentally friendly power production but entailing growing issues in power grids management [1,2]. The reliable integration of renewable sources of electricity is complex, partly because it implies changes in the vitally important activity of electricity provision, and partly because some renewable energy technologies pose additional challenges. Many works assess the possibility and the implications of a totally renewable energy system [2,3]. However, well before a complete transition to renewables, increasing the RES fraction to high penetration levels - as foreseen by environmental policies - arises many issues. A reference target is for instance set in the IEA Energy Technology Perspectives for 2050 [4,5], where the share of renewables is forecasted at 57÷71% of the global electricity

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List of acronyms

CAES	Compressed Air Energy Storage
EES	Electric Energy Storage
HES	Hydrogen-base Energy Storage
P2G	Power-to-Gas
PHS	Pumped-Hydro Energy Storage
RES	Renewable Energy Sources
TSO	Transmission System Operator

production, mostly relying on wind and solar power, if the international community will pursue a strong CO_2 emissions reduction policy ("*2DS*" and "*2DS-HiRen*" scenarios). Such a large amount of installed non-dispatchable RES capacity tends to cause a strong mismatch between electricity production and load, yielding issues for the management of RES energy lack or excess. A first option to cope with such issues is the adoption of a more flexible generation system involving traditional technologies with improved start-up and load following capabilities, able to compensate for sudden RES production changes. According to this viewpoint, more and more flexible combined cycle power plants are being developed and deployed by the power industry [6,7] and a higher number of simple cycle gas turbines might be introduced in the generation park, alone or in association with innovative systems [8,9]. Anyway, this solution is not able to recover excess energy. The second alternative are energy storage systems (ES), currently strongly developed in several countries [10–15], but with few options for very large peak shaving (GWh scale) capability. Among them, pumped-hydro storage (PHS) plants and compressed air energy storage plants (CAES) are feasible solution for peak shaving and excess energy recovery, due to the possibility of handling both large power and energy capacities. However, the possibility to install these technologies is limited by the geographical location and availability of attractive sites, as well as by environmental impact and social acceptance issues. Moreover, they are capital-intensive investments with a low modularity. Another research field involves hydrogen-based energy storage systems (HES), adopting electrolysis devices, which are nowadays considered a promising solution to support PHS and CAES for large scale energy storage [10,16,17]. An advantage of hydrogen technologies (and Synthetic Natural Gas ones) is the capacity of storing large amount of energy for long time, contributing also to manage load and production variability and grid frequency control. Usually, HES make use of Power-to-Gas (P2G) conversion systems (nominally, electrolysers) that convert excess or low cost electric energy in hydrogen heating value; in recent times, this terminology was extended and refers to the technologies aimed to convert renewable energy in hydrogen, for mobility, industrial applications, synthetic fuel production or reconversion to electricity (Power-to-Power). In addition to long-term storage and excess energy recovery, fast response electrochemical devices can also provide ancillary services (i.e. frequency and voltage control), resulting in positive effects on the grid and additional revenues for the P2G system [18]. The general concept of Power-to-Gas and its possible integration in the energy system is outlined in Fig. 1, while a review of possible process chains of different P2G paths, including different transformation technologies, the optional methanation step, distribution options and geological storage options as well as end-user applications can be found in Ref. [19].

P2G devices are modular, allowing the installation of new capacity with gradual investment, and compatible with a geographically distributed deployment, concentrated on the locations where issues of grid balancing are stronger. Drawbacks are mainly related with high specific costs and still uncertain lifetime under strongly unsteady operation; nevertheless, the foreseen evolution in next years could solve such issues and allow HES to contribute to the solution of the challenges posed by high renewable scenarios.

In this work, distributed electrolysis system (or Power-to-Gas, P2G) is supposed to be integrated in the electrical system of a country in order to shave peaks of wind and solar production that exceed the simultaneous load. The time horizon is very long (e.g. 2050) in order to investigate the effects of a high penetration of RES and the presence of large quantities of excess energy to be stored. The final use of the produced hydrogen (natural gas substitution for thermal purposes, industrial feedstock or fuel for mobility) is not specifically addressed, but compared with the expected size of the different energy sectors. After a brief presentation of the general methodology, the case of Italy is analyzed in order to verify the potential of P2G technology in the foreseen scenarios, approaching the problem from the point of view of the global system. A comparison with case of Germany – a country where a great deal of effort has been put in last years in developing and demonstrate P2G technologies – is then setup on the same basis. The comparison allows to evidence differences due to the diverse potential of RES and structure of the energy grids as well as in the reachable target application of this technology.

Long-term analysis concept

This work focuses on future energy systems where RES installed capacity is -at least to some extent- higher than the minimum electric load, with the possibility of a frequent full load coverage by non-dispatchable energy sources. The timeframe will be frequently addressed making reference to the year 2050, which is set as representative of a long-term time horizon. In this scenario, the goal is the assessment of P2G systems impact on this type of energy system and the estimation of the amount of hydrogen generated through P2G, whose final use could be primarily in the mobility field (feeding fuel cell electric vehicles) or related to industrial and thermal sectors. The long-term time horizon makes extremely difficult an estimation of the installed capacities of both conventional and innovative technologies, since they depend on the evolution of economics, politics, regulatory policies and technology improvements along several decades – a matter which can hardly be foreseen. Many studies defining future 'scenarios' related to this topic are periodically published and updated as a support to policy makers (such as IEA Energy Perspectives [4]) by international and governmental agencies. In this work, rather than relying on the combination of a specific economic, political and technologic scenario, a

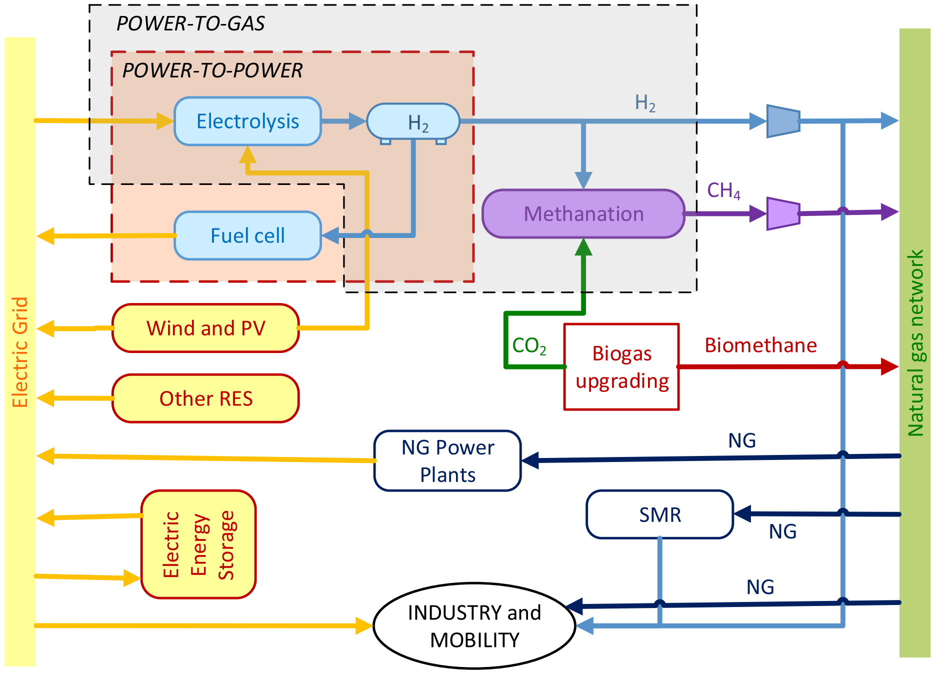

Fig. 1 – Energy pathways of Power-to-Gas and interactions with energy infrastructure.

different approach is applied, similar to the one already presented in Ref. [20], where the analysis aims at investigating a situation where the installation of RES is pushed at the upper technical limit or 'technical potential'. The analysis focuses on wind and PV and, based on geographical and physical constraints, as well as on some assumptions on the technology evolution, evidences their maximum reasonable installation potential at a country-scale. Then, the resulting energy share will evidence the necessity of the P2G technology as well as its limits in terms of capacity, leaving room for integration of different storage options. The technical potential could result in substantially higher installed RES capacities with respect to the electric peak load. Even so, the objectives of total load coverage by RES (as well as the target of a 60%–90% coverage of total energy consumptions – electrical and non-electrical – that is frequently mentioned by policy makers and international agreements, such as the European Roadmap [21]) could not be reached because of the low equivalent operating hours of these technologies. The requirement of energy storage for peak shaving, allowing to distribute very high but short electrical power generation peaks on much longer periods of actual demand, is then evident. Obviously, this theoretical threshold of installed RES could turn out to be too high to be reached due to a number of factors (including the effect of economics as well as of political and regulatory decisions). So that a sensibility analysis checking the results at different levels of RES penetration contributes to understanding which are the reasonable objectives for the P2G technology in the pathway towards high-RES energy systems.

Residual load methodology

The methodology is based on the concept of residual load, namely the fraction of the load that conventional (or controllable RES) should cover once the contribution of wind and solar production is given, assuming they have priority dispatch. The energy balance of the electrical system is calculated hour by hour. Residual load RL for each hour t is defined as the difference between the foreseen load L (total electricity demand) and the production from renewable energy sources (Eq. (1)). A positive residual load implies the need of traditional energy sources in order to fulfill grid (and thus customers') consumptions. A negative residual load is determined when the available renewable energy cannot be fully consumed by the customers connected to the grid, so that an excess amount (corresponding to the absolute value of the residual load) can be fed to a storage system, which in this work is considered to be the P2G system. We do not consider alternative large-scale energy storage technologies (e.g. pumped hydro, whose capacity is heavily limited by geophysical constraints); and since the focus in on multi-GWh-scale systems, we also do not consider lower energy capacity technologies (e.g. batteries).

$$RL_t = L_t - E_{wind,t} - E_{sun,\,t} - E_{hydro,\,t} - E_{geoth,\,t} \tag{1}$$

In this preliminary estimation, no balancing actions are included (i.e. ancillary services for grid stability and compensation of the mismatch between planned and actual production corrections), that are instead the object of a diverse approach. The analysis is based on ex-post data on hourly production and load profiles available from transmission system operator (TSO) websites (*Transparency reports*, European Regulation 1228/2013); scale-up assumptions with respect to the installed renewable power capacity are also included in the model. In general, wind and solar productions are linearly scaled up to their technical potential (calculated in reference studies depending on geography, meteorology, landscape constraints and technological factors):

$$E_{i,t} = E_{i,t}^{ref\quad year} \cdot \frac{P_i}{P_i^{ref\quad year}} \tag{2}$$

where $E_{i,t}$ is the energy produced by technology i at time t and P_i the total installed capacity. This approach results in constant yearly equivalent operating hours for the technology, preserving also the correlation between load (for which the same rule can be applied) and production profiles; the results can then be checked against different reference time series. In further analysis, scale up is limited to unpredictable energy sources, since P2G solutions aim at consuming excess electricity. Feeding a P2G plant with electric energy from traditional plants (as well as from biomass, WTE or other ‘fuel based’ sources) would be a non-sense due to the intermediate steps efficiencies (i.e. direct hydrogen production from fossil or biofuels is much more efficient). Therefore, the model estimates the energy from traditional power plants required to match the load curve only in case of insufficient RES production. An example is provided in Fig. 1, in which the current energy production share is scaled according to the described rules. Hydro and wind power installed capacities are doubled, while installed PV power is three times the original one. At peak times, the energy production from RES exceeds the load and is partially recovered by P2G (up to the maximum installed capacity). The exceeding fraction could be stored and used to cover part of the residual load (peak shaving), otherwise satisfied by traditional technologies.

An example of the profiles resulting from this approach is given in Fig. 2.

Excess energy from negative RL periods can be stored by a power-to-gas system in chemical bonds of high-value fuels such as hydrogen. Anyway, the conversion efficiency and the economics have to be considered. Given a fixed P2G installed capacity, hydrogen produced hour-by-hour can be calculated, assuming that all power exceeding the electrolysis capacity is anyway lost (cutting generation through wind turbines parking, PV plant separation from the grid etc.). Electrolysis system efficiency is assumed constant and equal to $70\%_{LHV}$ [22], making reference to the average performances of state-of-the-art electrolyzers either based on alkaline or PEM processes [23]; energy values are then converted to hydrogen mass through the lower heating value (120 MJ/kg_{H_2}). Constant efficiency is a reasonable assumption taking into account the presence of opposite effects of electrochemical efficiency increase and higher impact of auxiliaries at partial load; moreover, the modularity of P2G systems allows to shut-down part of the units at part-load, avoiding to suffer from higher (in relative terms) auxiliary consumptions. It is then possible to avoid using a more detailed efficiency model for the purpose of a global energy system analysis, as performed in this work. The total installed capacity can be then varied in order to investigate its effects and the possibility to reach a given minimum number of full load hours or equivalent operating hours, which are a first general indicator of the expected remuneration of the investment needed to setup the P2G system. A reference breakeven point for P2G is initially set to 1000 full load hours [24], performing a sensitivity analysis in order to check the influence on the results; while postponing a more detailed estimate of economics, that is not meaningful for long-term horizons.

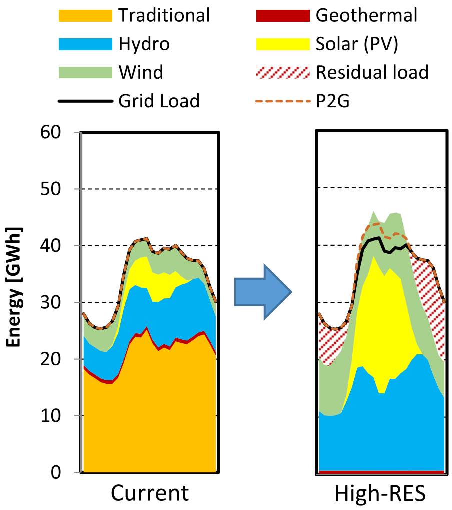

Fig. 2 — Example of one-day RES installed capacity scaling (double hydro and wind, three times solar). Excess energy can be recovered by PG2 up to the maximum installed capacity; the remaining can cover part of the residual load (peak shaving). The final residual load is satisfied by traditional technologies.

Energy system operation data are collected in a SQL database that is queried by a VBA Excel macro, which performs the abovementioned hour-by-hour calculations and optimizes the size of the P2G system while fulfilling a given target of minimum operating hours; preliminary reconciliation of TSO data is applied to check for missing or not realistic values. When multiple zones are included in the model, in the first step, the code evaluates each zone alone and then uses zonal excess energy to cover any lack of energy in other zones, considering cross-zonal transmission limits and losses.

Case study: Italy

The Italian electric system is strongly interconnected with the European grid and exhibits some peculiarities with respect to other adjacent countries. The country energy mix, depicted in Fig. 3 from TSO data (TERNA, [25]), has a strong component of thermal power plants, whose contribution is decreasing in last years due to the increasing contribution of wind and solar power. Contribution of hydro power plants is stable due to the saturation of suitable sites for dams and increases mainly due to repowering and run-of-the-river plants. A relevant portion of electricity demand is satisfied by import. No nuclear plants are in operation in Italy and the contribution of coal and oil is limited (about 20% of installed thermal power), leading to a pretty flexible system. General data relates to 2015 despite in the following analysis 2013 production profiles will be adopted because of lack of detailed data for 2014 and 2015. Anyway, the situation has not changed significantly with respect to the installed capacity: some thermal plants have been dismissed

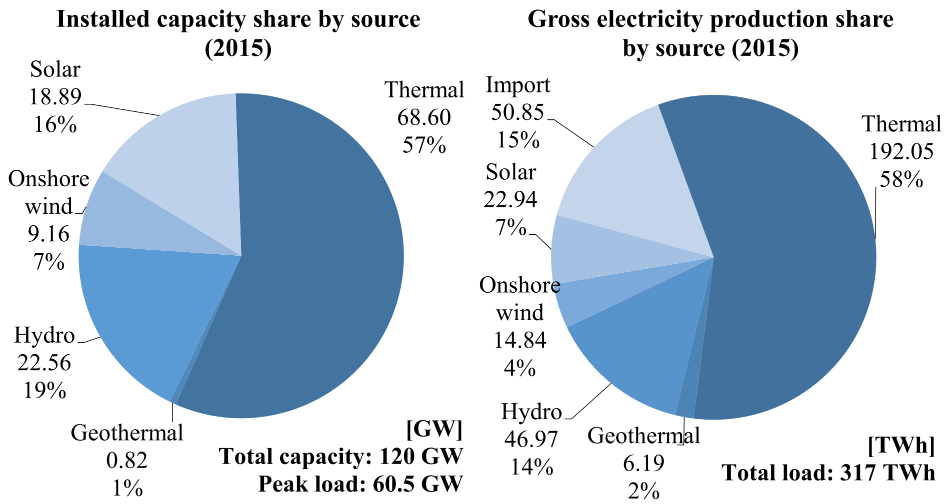

Fig. 3 – Italian electricity production mix by source. Installed capacity and electricity production referred to 2015 [25].

and solar and wind have experienced a small increase. In the same way, energy production share did not change; the most relevant change is in hydro plants that changes between 40 and 60 TWh depending on yearly climate, while other contributions are practically unchanged.

Different options for electricity generation are grouped according to the classification of data in databases of TERNA [25,26]; this simplification is suitable for the general energetic evaluations of this section that neglects dynamics and response time of technologies.

An example of energy production share for one week is presented in Fig. 4. Multiple-peaks daily trends are evident, as well as the load reduction in the weekend. Randomness of wind production can be observed, while production from solar is concentrated in the middle of the day with steep changes in the morning and in the evening that have to be managed by traditional systems. If more weeks are investigated in detail, seasonality of consumption and RES production becomes also evident. Moreover, it can be noticed that in some conditions, the load is already largely covered by renewable energy sources. These general observations will be useful later for the discussion of the impact of assumptions on the results of the model.

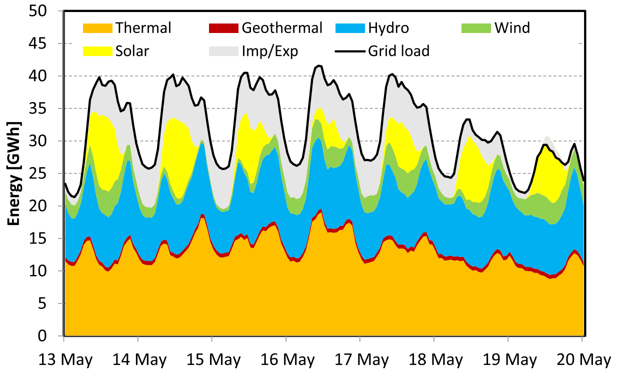

Fig. 4 – Hourly electricity production share by source for the week 13–19 May 2013. Data source: TERNA (TSO) website [26].

Another peculiarity of the Italian system is the zonal management of the electricity market that reflects the intrinsic structure of the transmission grid. The stretched shape of the country limits the possibility of deploying a meshed grid in the central regions and, as a consequence, tends to cap the transmission capacity between North and South. This aspect has a non-negligible impact on the potential of energy storage systems, as discussed afterwards.

Load data and foreseen evolution

Load profiles are the first input required by the model; their future evolution could match several scenarios. Demand trend shows a strong reduction of electric energy consumption in Italy in the last years (about −6% from 2008) with some uncertain signs of recovery [27]. However, this reduction is mainly due to the crisis in the industrial compartment and general economy which has featured the last decade, more than to energy efficiency actions, which in any case are increasingly carried out; future trend is therefore strongly related to the evolution of economics. Moreover, on a long-term basis, to which this work is focused, an electrification of thermal and mobility sectors is foreseen with a consequent additional electric load. Nevertheless, this aspect is still not relevant in the two alternative scenarios that are available from TSO analyses [28], based on medium-term forecast:

i. The first one considers an increase of electricity demand equal to about 1.2% per year, according to historical trends and GDP evolution forecasts. The growth of the industrial sector would be about +0.2% per year, of the domestic +0.8% per year, of the tertiary sector +2.9%, while agricultural sector is almost constant. This scenario would lead to an electric demand of about 380 TWh in 2022.
ii. The alternative scenario, which considers much stronger energy efficiency actions (together with more conservative hypothesis on the economic outlook) limits the increase of

the load in 2022 to about 0.5% of the current one; so that in this case, the load in the next decade would be essentially constant. The hypothesis is a slow economic recovery, strong energy efficiency measures and slow evolution of power technologies.

These scenarios are considered representative despite their horizon is limited to 2022, because of the uncertainty in long-term forecast and the trend is therefore extrapolated, with an approach coherent with ETSOE-E vision 1 (±0.5%). The second assumption (constant load) is chosen as the reference case in further calculation, whereas the influence of a different (higher) energy demand is considered in the sensitivity analysis.

RES estimated technical potential

Many works address the foreseen installed capacity of RES in next years. Nevertheless, they are usually focused on market evolution; resulting predictions are therefore affected by economic and political considerations. As already mentioned in the introduction to this paper, a more general analysis of RES technical potential should not take into account these aspects, but only limitations due to available resources and environment safeguard. Moreover, we limit discussion to wind and solar plants, while geothermal and hydro capacities are considered constant, mainly because of the low additional potential that can be exploited in Italy. A review of available data in literature considering the technical potential is summarized in Fig. 5 where the differences between the foreseen evolution of the installed capacity are evidenced.

Technical potential for wind in Italy was assessed by several studies [28–33]; however, they present different assumptions and pretty different results. Nevertheless, they are somehow influenced by economic evaluation and limited due to the short time horizon, or based on an old reference turbine technology, so that results can be considered not up-to-date and not highly representative. The ANEV (national association of wind power industries) report [30,31] and RESHAPE Project [32] figures are the most focused on a specific definition of the technical potential, considering also environmental conservation issues (i.e. presence of natural reserves, landscape protection) and technical limitations (i.e. orography constraints). Protected areas, urban areas and artificial surfaces (e.g. roads) are excluded by potential plants locations, as well as rivers, lakes and non-usable surfaces (i.e. glaciers, cliffs, mountainous terrain).

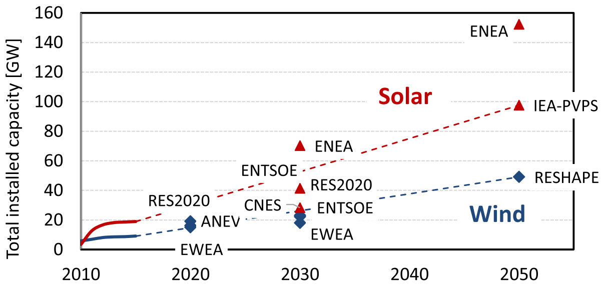

Fig. 5 – Expected evolution of technical potential for wind and solar technologies according to several studies (EWEA [29], ENTSOE [28], ANEV [30,31], RESHAPE [32], RES2020 [33], IEA [34], ENEA [35], CNES [36]).

An alternative approach is calculating the effects of rescaling the current installed units to the state-of-the-art, assuming that the optimal locations for plants are in most cases already in use and that the power increase is due to better exploitation of the resource and installation of new machines in place of older ones. Assuming a repowering of the current average turbines (1.36 MW [31]) with the largest state-of-the-art technology (Enercon E126, 7.5 MW, onshore), the potential for installed capacity is 47.24 GW; this figure is very close to the high-density scenario evaluated by the RESHAPE Project (49.1 GW), which is also the one with more reasonable assumptions in terms of technical potential evaluation. Therefore, this value is assumed as long-term reference in the evaluations carried out in this work.

It must be highlighted that all the mentioned studies neglect the presence of off-shore installed power in Italy, or limit its contribution to pretty low values (less than 1 GW). This hypothesis can be justified by the fact that optimal Italy's marine locations for wind parks are generally featuring much deeper waters than currently admissible for state-of-the-art offshore wind power installations (e.g. typically installed in <10–30 m water [37] like in most exploited sites of the North Sea). Therefore, in the further analysis, only on-shore wind power plants are considered. Future availability of deep water offshore wind power technologies, presently under R&D (e.g. floating wind power stations), could open the way to a much higher technical potential (or make the evaluation assumed here more conservative).

As far as the evaluation of the solar technical potential is concerned, the analysis is complicated by the large number of assumptions required to define the actual available surfaces and the reduced number of comprehensive studies which have been published so far. The most reliable data result from IEA [34], that estimates available surfaces on buildings and ground; the annual energy production is then calculated and converted to installed capacity assuming an average value for full load hours (i.e. 1300 h for Italy), resulting in about 97.62 GW of installed photovoltaic systems. Moreover, the surface considered available for PV is much lower than the total surface currently used for buildings (about 1050 km^2 vs. 7300 km^2 [38]), which makes the estimation reasonable; it is the value considered in baseline scenario of this work. The same order of magnitude (1828 km^2) for surfaces occupied by PV in 2050 is given by a study of ENEA [35], corresponding however to an installed capacity of 152.3 GW.

P2G potential and sensitivity analysis

Discussion of the P2G potential will follow a range of scenarios that are defined in advance in Table 1. The idea is to use the model on the current scenario and then evaluate the effect of increasing the installed capacity of both solar and wind, up to the technical potential previously assessed ('Base' case). The results can be then affected by different assumptions whose influence is checked: the evolution of total electricity demand (scenario #1), the share between solar and wind technologies

Table 1 – Summary of hypothesis for simulated scenario.

Scenario		Time horizon	Wind capacity (GW)	Solar capacity (GW)	Electric load (TWh)	Grid limits (zonal)	Reference time series (year)
Current	Current energy system	Today	8.7	18.6	290	No	2013
Base	Technical potential exploited	2050	49.1	97.6	290	No	2013
#1	Increased energy demand	2050	49.1	97.6	350	No	2013
#2	Only wind capacity increased	2050	49.1	18.6	290	No	2013
#3	Only solar capacity increased	2050	8.7	97.6	290	No	2013
#4	Include limits on transmission grid	2050	49.1	97.6	290	Yes	2013

(scenarios #2 and #3) and the possible presence of limits of the transmission grid (scenario #4).

In all cases, an additional electric load is included, corresponding to the 'efficient scenario' presented in Load data and foreseen evolution section (0.5% yearly increase up to 2050); a strong reduction of electric demand is considered not realistic because of the contemporary presence of energy saving policies and the electrification process of mobility and thermal sectors. Further analysis will discuss the effects of a presence of wind-only or solar-only scenarios, where the different contemporaneity factor with the load could influence the excess energy available for energy storage or P2G, given the same yearly energy production. As discussed in Long-term analysis concept section, the time horizon specified in the table (2050) must be considered only indicative of a long-term high renewables scenario.

An example of electricity production share is shown in Fig. 6 for the 'Base' case (full deployment of solar and wind potential, coherently with the 2050 scenario of Fig. 5; load curve according to reference data series for the year 2013); two spring and summer weeks are selected since they feature large effects in terms of residual load. Some points have to be remarked. Due to the prevailing role of solar power, P2G contribution is always required in the middle of the day, when the contribution of PV is higher, facilitating the continuous operation of electrolysers during the day and a regular operation during the year. In the same hours, no contribution of traditional power plants is required. Moreover, the limit on minimum full load operating hours of electrolysers and the consequent limited installed power of P2G yields a significant quantity of additional excess energy, that could be exploited by other EES or allow an oversizing of the P2G system.

Results of the model previously discussed are summarized for several cases in Fig. 7. We remind here that the residual load is defined as the total electricity load [TWh/y] to be covered by power generation minus the production of renewables; in other terms, it is the quantity of requested

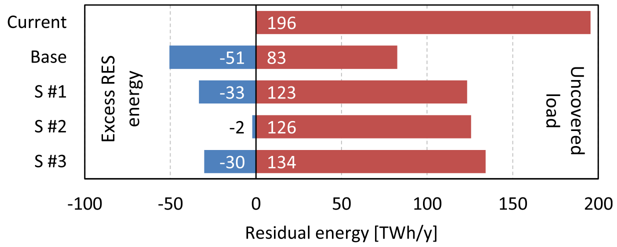

Fig. 7 – Estimated residual energy (electricity demand – renewable production) in current conditions, exploiting both wind and solar technical potential ('Base'), only wind technical potential (#2) or solar only (#3). Reference data series year 2013, load 290 TWh, max wind 49.1 GW, max solar 97.6 GW. Increased load up to 350 TWh is also considered (#1).

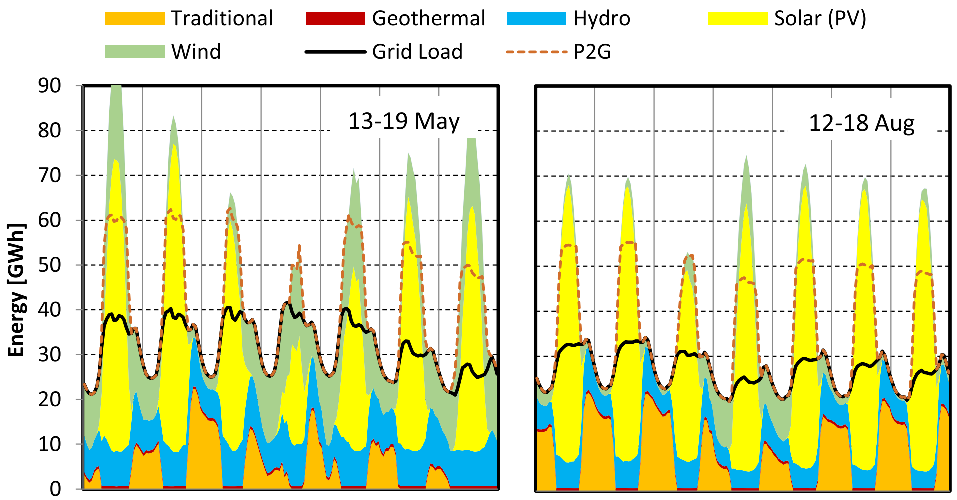

Fig. 6 – Hourly electricity production share by source and excess energy recovery. Detail of weeks 13–19 May and 12–18 August (Baseline data series year 2013, load 290 TWh, wind 49.1 GW, solar 97.6 GW).

electricity covered by non-renewables or conventional power plants. The residual load is calculated hour-by-hour and compared in different scenarios (see Table 1).

By way of comparison, also results given applying the model to current conditions (i.e. 2013 profiles) are calculated and reported in figure as "Current" scenario. In this case, the positive residual load is about 196 TWh per year over a global load of 290 TWh per year. If we move towards the foreseen exploitation of the technical potential (i.e. 'Base' case, wind 49.1 GW, solar 97.6 GW) residual load is more than halved, while a relevant amount of excess energy arises. This result is also related to the assumption of a constant load profile, as discussed in previous section; the impact is strongly reduced if the scenario with a net increase in electricity demand is considered (#1 in figure). On the contrary, the choice of different time series (e.g. 2012 or 2014 instead of 2013 data) has a tiny influence on the residuals, rejecting dependencies of the results on specific phenomena of a single year, as can be observed in Fig. 8. In 2015, hydro production was particularly low with respect to other periods, yielding a reduced contribution to load supply and therefore lower excess energy.

We can also consider the complete exploitation of wind potential alone (scenario #2); it yields to a small negative residual load, i.e. a small quantity of energy available for P2G, whereas the traditional sources contribution is reduced strongly to 126 TWh per year. On the other hand, a complete development of solar alone (scenario #3) leads to a significant negative residual load, mainly because of the higher technical potential estimated; nevertheless, the positive residual load is higher than previous case (i.e. 134 TWh/year).

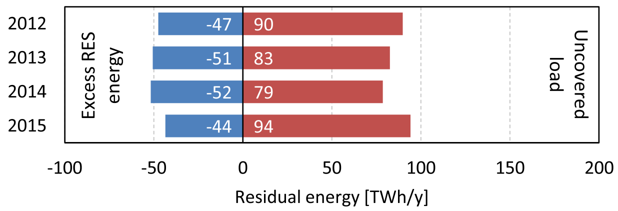

Fig. 8 – Comparison of results given by different reference time series scaled up to the technical potential (Load 290 TWh, wind 49.1 GW, solar 97.6 GW).

The situation can be justified by the very high peaks of solar that cannot be fully recovered with the P2G system, leading to high excess energy. Wind is much more intermittent, but it usually blows in periods of low load (i.e. evening, night, ...) resulting in even higher negative residual load. This effect is even more evident when both contributions are considered at the same time; the resulting available energy for energy storage systems (i.e. 51 TWh/year) is higher than the sum of single contributions (i.e. 32 TWh/year). An example of the different impact of wind and solar on P2G production is depicted in Fig. 9; two scenarios are considered, the one with predominant solar, the other with predominant wind power, but values of installed capacity are the same. The differences between the wind- and the solar-based scenarios will be discussed in further sensibility analyses.

Actually, input data of the model have a strong intrinsic uncertainty, due to the large scale of the problem and its dependence on several uncertain elements (i.e. weather variability, seasonality, economic cycles, etc.) as well as on projections of future technological development and economic strategies. A sensitivity analysis is consequently performed on time series, required equivalent operating hours, foreseen electricity demand and installed RES capacity.

Impact of installed P2G capacity

Once the results for residual load are set, the projected size of P2G system strongly depends on economics assumptions that are included in the model through the concept of minimum full-load operating hours. Due to the long time horizon covered by the analysis, it is not possible to perform detailed economic evaluations; however, a first target can be set at reaching a minimum full-load operation of 1000 h/year for the P2G system corresponding to the sizing criteria of current electrolysis system for stationary operation [24]. In addition, the EOH are checked as an index of competitiveness in a

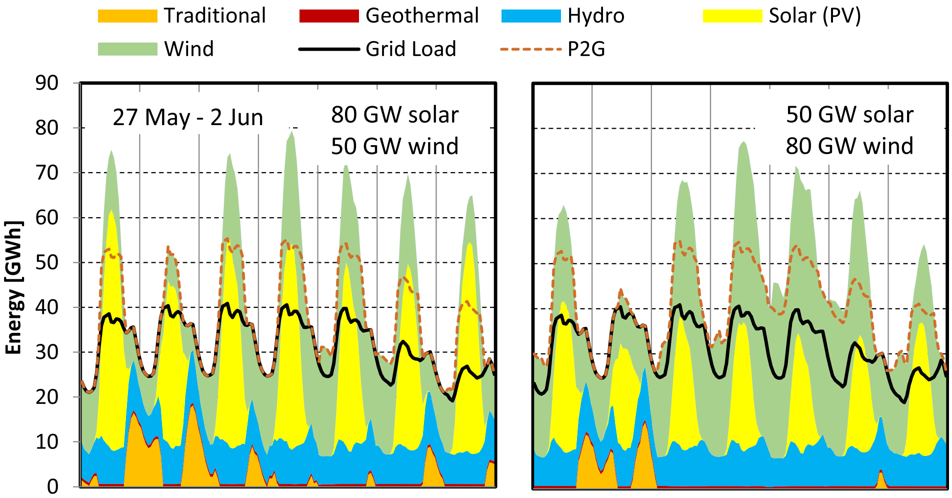

Fig. 9 – Hourly electricity production share by source and excess energy recovery. Comparison of a solar predominant scenario (left) with a wind predominant one (right) for the same week.

reasonable economic scenario, as well as the capability of the system of recovering the negative residual load. Fig. 10 reports total yearly hydrogen production from P2G and equivalent operating hours, which are strongly related to the installed capacity. Considering 1000 full load hours as reference, the installed capacity is about 22.1 GW (13% of the total RES installed capacity) and the consequent average equivalent operating hours (EOH) for the distributed P2G system is about 1800 h. The gap between equivalent operating hours and full load is remarkable, meaning that the system works frequently at partial load. Going over 50 GW of installed P2G capacity (30% of total installed RES capacity), the system becomes increasingly oversized and never works at full load; it can be seen that over 30 GW of installed capacity, the gain in hydrogen production becomes less and less attractive.

The recovery capacity becomes full only above nearly 40 GW of installed electrolysis capacity, an amount that is hardly reasonable as discussed before; consequently, it is evident the requirement of coexistence of different storage technologies (in particular, here peak-shaving storage technologies are the obvious choice).

Impact of electric energy demand

Another source of uncertainty is the foreseen evolution of the load; as already introduced, the reference assumption in the analysis is having a constant load in the next future, based on the concept that the strong effort in developing energy-efficient technologies – together with relatively slow economic growth - would compensate the increase of the net demand. As discussed in Load data and foreseen evolution section, a recovery of industrial sector would lead to an increase rate of the demand (as was typical before the recent years of economic crisis) with a remarkable effect on P2G potential.

It must be highlighted that the introduction of a large amount of electrical vehicles in the system is out of the subject of this dissertation; generally speaking, it could lead up to

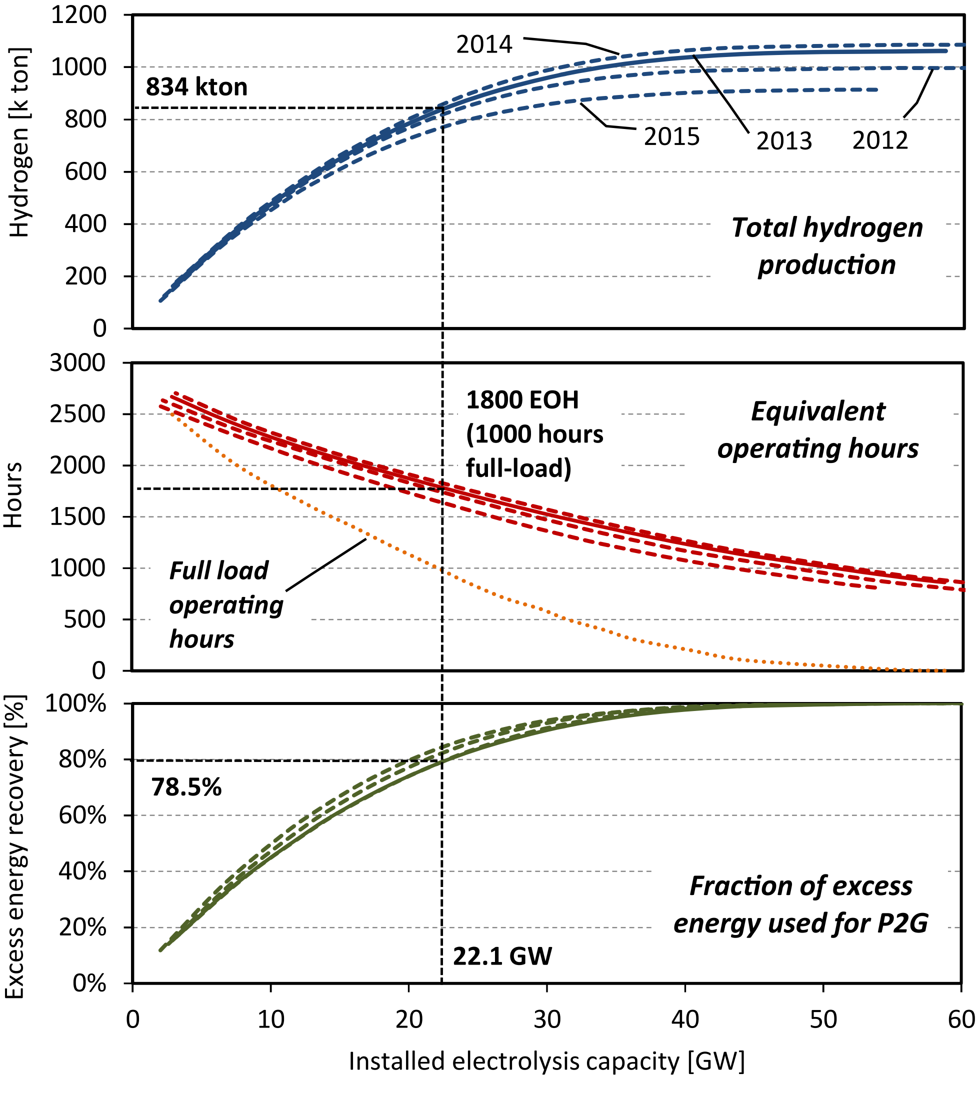

Fig. 10 – Hydrogen production, equivalent operating hours, full load hours and excess energy used for P2G as function of installed P2G capacity in the long-term 'Base' scenario (49 GW wind, 97 GW solar). Dotted lines for different reference time series.

over 400 TWh/y of total electricity demand [39], a figure that is comparable with the current size of the national electric system. In order to satisfy such a large new demand, the electric grid should be strongly repowered - if not rebuilt with a new one - and a greater production capacity (not existing in the assumed estimate) should be installed. Despite a large portion of the additional demand could be satisfied by distributed generation, new large power plants should anyway be included in the electric system, providing a strong contribution to power generation; depending on the production mix, the consequence is shifted towards a totally positive residual load, with smaller – or even negligible – potential for P2G. Nevertheless, it has to be considered that this scenario is not credible and it is much more likely a scenario with a mix of electric, fuel cell and other “green” vehicles that avoids oversizing of the electrical infrastructure.

From the general point of view of EES, conventional power plants should supply a large amount of energy (i.e. the difference between positive and negative absolute values), also storing the negative residual load in order to cover hours with RES production shortage. The additional capacity should be provided by alternative RES sources or by CCS plants not considered in this study, because wind and solar technical potential would be already saturated; the option of conventional plant is not viable due to the objectives on CO_2 emission reduction.

Impact of RES potential

Least but not last, the strong variability of foreseen potential for RES installed capacity generates a corresponding uncertainty on the P2G potential. In order to check the influence of future RES capacity (and consequently the evolution of the energy storage requirement with installed RES capacity), the maps in Fig. 11 are built for the reference assumptions. Results in terms of residual load, required installed P2G capacity, as well as consequent EOH and hydrogen production are presented as a function of the RES capacity scenario (i.e. wind and solar installed capacity). As already discussed in the introduction, the technical potential could be too high to be reached for several reasons and therefore it is required to check the impact of different levels of RES capacity on the P2G system.

First, it is important to notice a region (grey in figure) where it is impossible to fulfill the full-load hours requirement (below approximately 70 GW of total installed RES capacity). Above this threshold, installed electrolysis capacity grows and, as already mentioned in the beginning of P2G potential and sensitivity analysis section, the combined contribution of solar and wind increases the storage requirement with respect to the sum of the two (considered separately). With respect to the equivalent operating hours, values tend to reduce their dependence from solar installed capacity, but not from wind power. The additional P2G power capacity, which can be installed thanks to an increase in solar plants, is than always well saturated, because of the frequent mismatch between production and load peaks. In fact, in case of predominant solar capacity, the P2G system is always operated in the middle of the day at full load; on the other hand, if wind power has a stronger role in the energy system, operation is more irregular and distributed, with more frequent part load operation periods.

From the point of view of the P2G system, these results indicate a more favorable situation in case of RES evolution with dominance of solar PV plants, thanks to the more stable operation required to the balancing system, that reduces the cycling stresses on all the P2G devices (electrolyzer as well as auxiliary systems). From the point of view of the grid and related electrical system, the presence of a storage device is much more critical in case of large wind installed power, where the system is called to a heavier flattening (or stabilizing) effect on energy production profiles.

Zonal analysis

As previously mentioned, the Italian electricity market has a zonal structure that mirrors grid limitations in transmission capacity among some geographical zones of the country. The border of ‘*electrical*’ zones is defined by TSO according to frequently congested lines as learned by experience. The maximum capacity that can be allocated for each border is calculated a priori applying an N-1 safety criterion [40] (i.e. the system has to be stable also in event of the failure of any of the components) and then sent to the market operator (GME [41]) as input for day-ahead market sessions. The grid configuration within a zone is usually strongly meshed, so that congestions internal to the zones have low probability and moderate impact; as a consequence, possible grid congestions are solved on the intraday market and balancing market in a shorter time horizon. This aspect, which was neglected in the previous analysis, can be included in the model in order to evaluate the impact of plants location on the actual potential for RES energy storage.

Strong discussions were ongoing in last years about the opportunity and efficiency of the development of the electrical grid versus the installation of local storage systems in case of high-RES scenarios. Differences between the two approaches are considered in this work, adopting a simplified approach to the network in order to quantify the technical impact of the two solutions. The basic assumptions (total installed capacity, P2G minimum operating hours) are the same that in previous ‘Base’ case. The six main zones of the Italian market are grouped in two macro-zones (North and South), performing an analysis of the geographical distribution of renewable capacity and load, in particular of sites suitable for wind plants (mainly located in the South) vs. the distribution of the load (mainly located in the North). Solar capacity is distributed more or less uniformly on the territory; the higher productivity of the plants in the South is compensated by a higher number of suitable sites for distributed generation in the North (i.e. civil and industrial building roofs etc.).

The geographic share of wind and solar power is assumed to be constant in time, considering that the distribution of the resource and the structure of the territory will not change strongly in the future. Moreover, the geographical distribution of the load is also assumed constant under the assumption of a countrywide stable distribution of population and industry.

It is possible to carry out the simulation with the same methodology of lumped evaluation already described above,

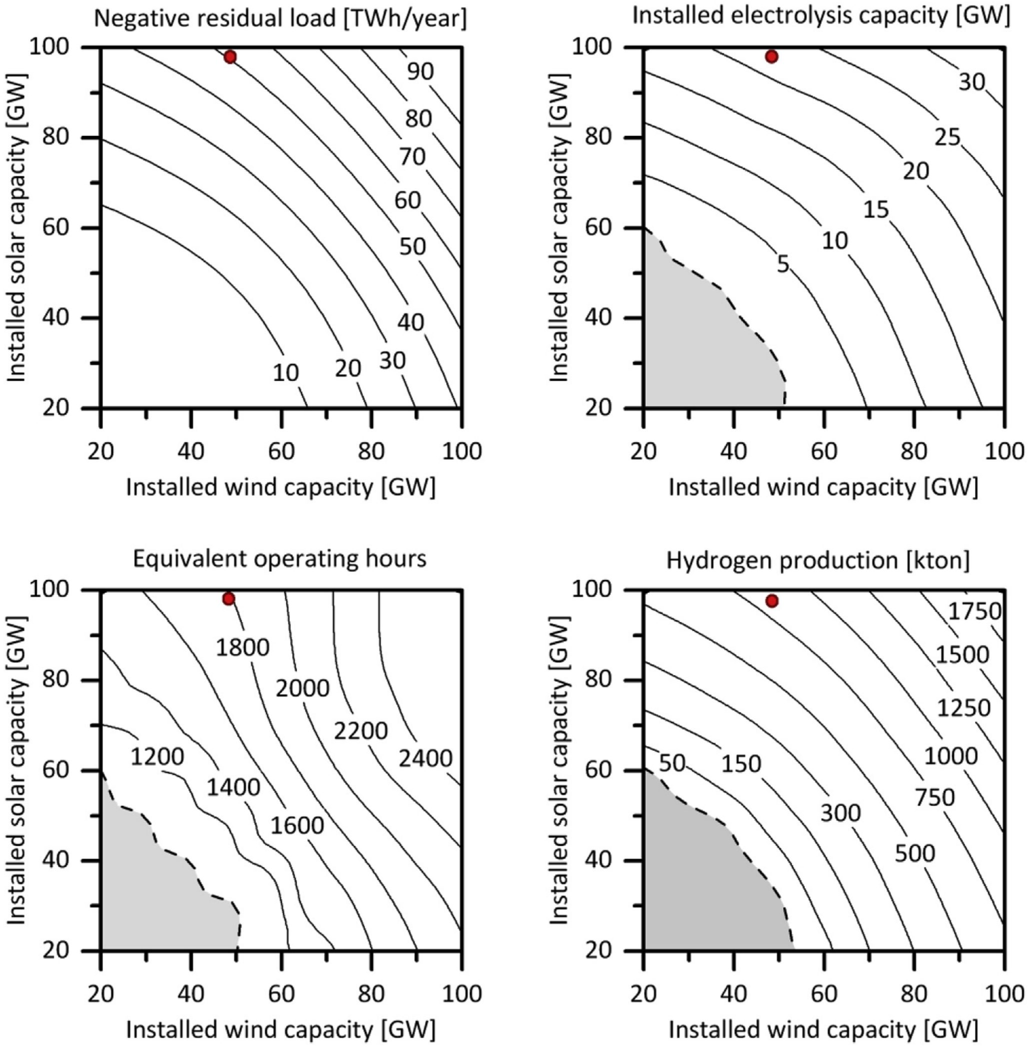

Fig. 11 – Residual energy available for electrolysis, optimal electrolysis capacity, equivalent operating hours and hydrogen production as function of the RES installed capacity (reference time series 2013, 1000 full load electrolysis hours, load 290 TWh/year). Evidenced gray region corresponding to no P2G installed. Reference case evidenced (red dot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with the modification of an hourly limit on energy transmission between zones, considering transmission losses equal to 6% of the input energy (corresponding to the current average of losses on the transmission system [25]).

Residual load is calculated separately for the two regions (A and B), according to

$$RL_t = L_t - P_{wind,t} - P_{sun,t} - P_{hydro,t} - P_{geoth,t} \pm P_{tr,t} \tag{3}$$

where the additional term P_{tr} accounts for the energy transferred between zones and is calculated as:

$$P_{tr,t} = \min(TL_t; -RL_{t,A}; RL_{t,B}) \cdot (1 - \varepsilon) \tag{4}$$

where ε are the transmission losses, TL_t the transmission limit and the sign accounts for the considered energy flow direction (A to B). In practice, the flow is limited by power lines capacity, by maximum excess energy available in the exporting region or by the maximum residual load in the importing zone. Electrolysis installed capacity, operating hours and produced hydrogen are then calculated according to the assumptions mentioned in the previous section, separately for each region.

Results for the baseline case (i.e. 1000 h full-load operation, RES potential completely exploited) are summarized in Fig. 12 and Table 2. Results are calculated as a function of the capacity of North-South interconnection, which is currently

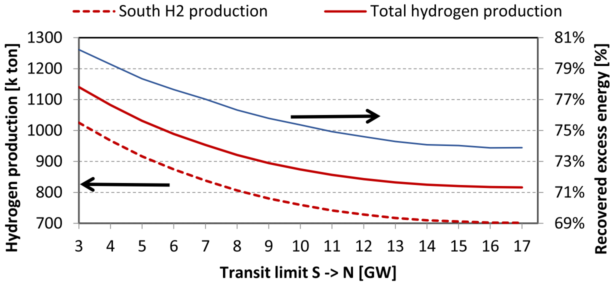

Fig. 12 – Effect of maximum energy transit limit from South to North on hydrogen production.

Table 2 – Comparison of P2G potential results for zonal approach.

		Transmission limit S → N [MW]		
		3000	5000	∞
Installed electrolysis capacity (North)	GW	4.5	4.5	4.5
Installed electrolysis capacity (South)	GW	17.8	17.3	16.6
Total installed electrolysis capacity	GW	22.3 (+5.7%)	21.8 (+3.3%)	21.1 (ref)
Negative residual load (North)	TWh/y	12.5	12.5	12.5
Negative residual load (South)	TWh/y	55.2	50.2	40.1
Positive residual load (North)	TWh/y	83.7	78.7	68.6
Positive residual load (South)	TWh/y	15.6	15.6	15.6
Hydrogen production (North)	kton/y	115	115	115
Hydrogen production (South)	kton/y	1026	916	701
Total hydrogen production	kton/y	1141 (+40%)	1031 (+26%)	816 (ref)
Recovered negative residual load	%	80.2	78.4	73.9
Electrolysis system EOH (North)	h/y	1211	1211	1211
Electrolysis system EOH (South)	h/y	2739	2524	2013

about 3000 MW, while the TSO improvement plan considers an increase up to 5000 MW in few years [28]. Values of about 17,000 MW are equivalent to an infinite capacity because the estimated peaks of transferrable energy are always lower; this value is therefore assumed as reference unconstrained case in the analysis.

As expected, the behavior of the two zones is opposite: in the North the residual load is prevalently positive, while the South exhibits an overproduction from RES. Negative residual load in the North, that is used by P2G systems, is independent from the transmission capacity limit and the resulting yearly amount is quite low (12.5 TWh/y). This outcome is due to the fact that hours with an overproduction in the North are below 1500 in one year and mainly in conjunction with overproduction in the South. This condition yields a low amount of hydrogen produced (about 115 kton/year) and a relatively low amount of equivalent operating hours for the P2G plant (about 1200 instead of 1800 in the lumped case). Situation of the South is opposite, with a low amount of positive residual load (about 15 TWh/year on 3000 h) and a large excess of RES power that is exported to the North.

P2G system sizing in the South is strongly related to the capacity of the system to export energy to the North. The current limits yield an increase of about 6% of the installed electrolysis capacity (that corresponds to a 40% increase of hydrogen production) with respect to the reference unconstrained case. Foreseen grid development would halve these estimates, but anyway the impact of transmission limits is not negligible. An interesting result of the zonal model is the evident difference in EOH between devices installed in North and in South, favoring the latter and leading to completely different economics, also with respect to the value obtained in the lumped approach (about 1800 EOH).[1]

The last quantity evaluated is the ability of the system to avoid wind energy losses, reported in Table 2 as the fraction of negative residual load that is recovered by the electrolysis system. The residual power has to be curtailed and therefore lost. Lower transmission capacity increases the amount of energy available for P2G system, but also the fraction that can be recovered (from 73.9% to 80.2%) because of the larger electrolysis installed capacity. The larger number of hours with excess RES production justifies the larger number of electrolysis units; the P2G system thus recovers additional energy in peak production hours, increasing the effectiveness of the system.

Impact on the energy system at national level

Results of the previous sections can be evaluated considering the size and the demand of the country's energy systems which are potentially impacted by P2G, i.e. the electric power system, the natural gas system and the mobility system.

First, the production can be compared with current size of the related energy markets; the total primary energy consumption in 2014 was about 167 Mtoe with a reduction (−3.8%) resulting from the combined effects of economic recession, energy efficiency policies and of changes in industrial sector. The demand is covered mainly by oil (34.4%) and natural gas (30.5%) with a strong contribution from RES (21.2%). The total net import was about 122.5 Mtoe (73.6%), configuring a large dependence of Italy on external energy supply [42].

In this framework, the P2G technology has theoretically a large potential in producing gaseous fuels from renewables (wind/solar). Aiming to evaluate this potential, a selection of significant results from previous simulations is summarized in Table 3. The first two scenarios reported in the table are baseline cases without grid limitations already discussed in P2G potential and sensitivity analysis section, considering the use of the whole RES technical potential, with two different limits for profitability of P2G (corresponding to 1800 and 1230 equivalent operating hours).

Considering P2G aimed at natural gas substitution, the hydrogen production could cover about 5–6% of the total primary energy needs, while if dedicated to mobility fuel supply the fraction can increase up to 6–8%. Also from the

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[1] Small gap between results of infinite grid capacity assumption and the lumped approach in P2G potential and sensitivity analysis section is due to the different structure of the simulation: the regional model takes into account the energy transfer between regions and the related losses. Moreover, the 1000 full load hours assumption is applied separately to the two groups of electrolysis devices.

Table 3 – Summary of simulated scenarios.

Scenarios	P2G capacity (GW)	Eq. hours (hours/y)	Hydrogen production (kton/y)	Primary energy (Mtoe/y)	Avoided emissions sNG/mobility[a] (Mton/y $CO_{2,eq}$)	Electric load covered by RES (% vertical load)
Base	22.1	1800	834	2.4	5.61/8.81	71.5%
	40.0	1230	1038	3.0	6.99/10.97	71.5%
High load	12.4	1430	372	1.1	2.50/3.93	62.7%
Grid limit	22.3	2430	1141	3.3	7.67/12.05	71.0%

[a] Two alternative options: substitution of natural gas for general purposes (sNG, 201.96 kg/MWh_{LHV} [43]) or substitution of fuel for mobility (on average 317 kg/MWh_{LHV} [43–45]).

point of view of emissions, the impact is higher in case of hydrogen production for mobility, with about 8–11% reduction of emissions vs. 4–5% in case of NG substitution.

The third case ("High load") considers a further increase in total electric load, which leads to a different potential for P2G given the same installed RES capacity, as discussed in Impact of electric energy demand section. The presented high load scenario reduces the impact on energy supply to about 2–3% (2–4% on emissions). The opposite case (electric load reduction) would be the most favorable, even though not very probable.

The last case (grid limit), instead considers a persistence of transmission lines capacity limits (e.g. due to politic, environmental and social issues) that separate RES generation from loads. This case yields results which are comparable with the second one from the point of view of impact on energy system, but with a smaller installed capacity and a higher utilization factor of the P2G system.

When applied to the mobility sector, the energy supply potential can be translated in terms of number of vehicles fed by P2G fuel. The resulting fueling capacity could cover the yearly consumption about 6.5 millions cars (12,000 km/year, 1 kg_{H_2}/100 km [24]) or, alternatively, 95 thousand buses (60,000 km/year, 14 kg_{H_2}/100 km [24]). It is interesting to note that, when compared with the current size of the transport system, these results yield a remarkable although limited impact on car sector (17%), while the public transport (buses) could be almost completely covered by hydrogen from P2G. It should be anyway recalled that these results consider only P2G fed by excess energy from RES dedicated to electricity production – i.e. hydrogen is a kind of by-product of electricity generation and RES management – and not specific fuel production infrastructure (i.e. RES dedicated exclusively to fuel production). The contribution of additional RES installed capacity and of greening natural gas (or fuels for mobility) to primary energy import and emissions reduction can be also compared with the general national and European objectives (Italian SEN 2020 [42], EU Roadmap 2050 [21]).

Specifically, the *European Roadmap 2050* (2011) sets the reference long-term framework for national policies with a challenging objective of 80–95% decarbonization of European economy with respect to 1990 levels; the roadmap contains no specific rules or actions but suggestions and scenarios. Italy applied it on a mid-term horizon with the SEN (National Energy Strategy, 2013), setting goals for 2020 which are more restrictive with respect to *2020 Climate and Energy Package* European directive (Italy met the 2020 objectives some years in advance [46]).

In this framework, P2G shows a potential on long-term horizon;

- the exploitation of technical potential for renewables, assumed as reference for previous calculation, corresponds to about 70% of the electricity production from RES. This threshold is next to objectives for 2050 (75% electricity production from RES). In this scenario, a reduction of emissions of about 280 Mton is required and balancing systems based on P2G could contribute to about 4% to the total emission reduction target.
- future scenarios with a general electrification of the energy systems (i.e. heat pumps, electric cookers) could lead to the *high load* scenario, with a reduced relevance of P2G. Anyway, the foreseen energy efficiency measures should compensate the increase of the load, leading to a stable situation the on electrical grid. A completely different scenario raises in case of large penetration of electrical mobility.

Considering middle-term objectives (2020), the analysis shows the requirement of nearly 40 GW of wind + solar installed capacity (13 GW more than 2013 values) in order to reach the threshold of 38% electricity production from RES. This value is not sufficient to justify the implementation of a P2G system, due to the resulting limited number of operating hours purely based on excess RES energy (see Fig. 11). On the other hand, P2G could be anyway an economically viable solution for solving local or intra-zonal balancing issues; moreover, it would become increasingly attractive in case of a specific development of hydrogen mobility that requires large quantities of "green" CO_2-free hydrogen, together with a possible production from biomass.

Considerations concerning curtailments

In addition to recovering power from negative residual loads, P2G con usefully exploit electricity coming from wind park curtailments, which may happen due to local grid saturation. The current situation of the Italian electric system never produces conditions where the load is completely satisfied by RES; however, recently and in rare hours, the market of a single zone (specific South regions in midsummer) happened to be completely saturated by RES, although the overproduction was totally absorbed by the nearest regions.

Within this framework, wind park owners can anyway be subjected to TSO curtailment orders that limit their production, where these 'out of the market' orders find a technical explanation in local stability issues of the transmission grid. This type of issues grew remarkably in the last decade, when the fast growth of installed wind power capacity, parallel to the massive solar installations, was not followed by a simultaneous improvement of electrical grid capacity, also because of the difficult authorization process and the related high investment costs. Moreover, most of the wind potential is situated in Southern regions whose electrical grid is historically weaker than in other parts of the country because of the absence of strong loads. The amount of curtailed energy is counted as MPE ('*Mancata Produzione Eolica*', missed production from wind) and refunded to producers. The resulting cost is covered by the community through the electricity tariff and, therefore, it is reasonable that it will be no longer applied when RES will reach grid parity. In this case, this cost will be included as a risk in wind farms business cases. Fig. 13 shows some general statistics about the yearly amount of curtailed energy (MPE).

The trend is negative until 2013, because of the improvements in local transmission lines; the impact on the system was reduced from 11% of wind production in 2009 to about 1.5% in 2012. In 2013 the curtailed energy is growing again, mainly because of congestions on HHV primary transmission lines [47]. In last years the value is more or less stable. Initially, wind power plants were put out of production due to congestions on local lines (73% of missed production). In last years, the main issue became the limitation in power transfer from South to North by means of high voltage lines (51% of missed production); local congestions keep anyway a relevant role (25%). MPE is concentrated mainly in two regions: Campania (from 30% to 57%) and Puglia (from 60% to 40%).

This phenomenon could generate a potential capacity and application for P2G systems in case of future changes in regulation and cancellation of refunding procedures for MPE.

A rough estimate of hydrogen production from this non-dispatchable energy evidences that the order of magnitude of impact on current natural gas consumption is very low (well below 0.5%) both as a national average and within the regional framework. Nevertheless, the future increase of installed wind power could evidence growing issues related to grid capacity, whose extension is intrinsically slower, widening the space for P2G application.

Comparison with Germany

A comparison with the case of a different country allows to catch the influence of geographical location, as well as of the different distributions of electric load and RES availability, on the conclusions which were previously drawn. The choice of Germany is due to the large effort currently spent in this country for the design and demonstration of P2G plants, in addition to an ambitious H_2-mobility deployment roadmap.

The same approach described in this work was implemented by FZJ IEK-3 [51] in order to estimate the potential for P2G in Germany on a long-term horizon [24]. Calculations are based on quarter-hour data provided by TSOs [52] for wind and PV feed-in, coupled with grid load, linearly rescaled in order to match the total foreseen installed capacity.

The model used here for Germany is run under the same assumptions of the mentioned FZJ IEK-3 study:

i. constant number of installed wind turbines onshore with respect to reference, rescaled up to the state-of-the-art single turbine capacity (7.5 MW) yielding about 167 GW of installed capacity
ii. expansion of off-shore installed wind capacity to 70 GW with 4000 equivalent hours per year
iii. PV installed capacity is maintained at the same level of reference case; increase in wind installed capacity is considered more attractive with respect to PV
iv. other RES are kept at the same level of the reference case, because of the lack of additional potential (i.e. new locations for hydro) or low contribution (i.e. geothermal); biomass and WTE plants are not discussed here because they are fully programmable and can contribute to positive residual load balancing, instead of providing negative residual useful for P2G
v. electrolysers with $70\%_{LHV}$ efficiency and at least 1000 full-load hours in order to evaluate their installed capacity

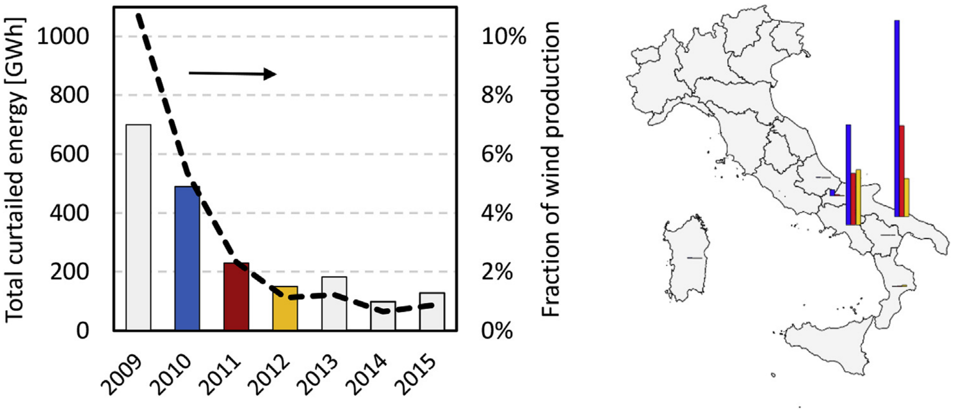


Fig. 13 – Evolution of MPE in last years and impact on the total production of wind power plants [47]. Geographical positioning of curtailments (data available 2010–2012) [48–50].

vi. excess wind (over the assumed electrolysis capacity) is curtailed

The results are comparable with the literature ones, validating the implementation of the model; they show a production potential of about 5.4 Mton$_{H_2}$ in connection with 83 GW installed electrolysis capacity and 275 TWh/y excess energy available for electrolysis and storage. Some additional evaluations are performed in order to compare the results with the case of Italy, as reported in Fig. 14.

As it can be observed, the P2G potential for Germany is higher than for Italy, despite nowadays the impact of residual load covered by non-renewable energy sources is much higher:

- in the Italian long-term case ("Baseline" in Tables 1 and 3), where 71% of electric load is covered by RES, negative residual load is recovered by a factor 78% with an installed electrolysis capacity of 22 GW, that is about 15% of wind + solar installed capacity;
- in Germany, where within the same timeframe 86% of electric load is covered by RES, a 93% excess energy recovery is obtained with an installed electrolysis capacity of 84 GW, which is nearly 41% of RES capacity.

The German long-term case of Fig. 14 is obtained with the assumption of a stable PV installed capacity, which may turn out to be quite restrictive, but is considered for coherence with reference estimates [24]. Due to that, in addition to reference cases and long-term expected technical potential exploitation, a fifth case is included in the analysis ('*high PV*' case), considering an increase in PV installed capacity corresponding to the figures reported in a recent perspective study [53].

A deeper understanding of the comparison can be obtained considering the different share of renewables with respect to the peak load featured by the two countries, as shown in Fig. 15.

As it can be noticed, the German system already shows a ratio of installed capacity over peak load above 88% in 2013 (neglecting the coincidence factor among load, solar and wind production issues). Italian case starts from a 55% share (27 GW of wind and solar over 49 GW of peak load). Nevertheless, from the point of view of useful energy, RES currently cover in both cases about 32% of the total electric energy demand, i.e. the average utilization factor of the RES mix is higher in Italy than in Germany.

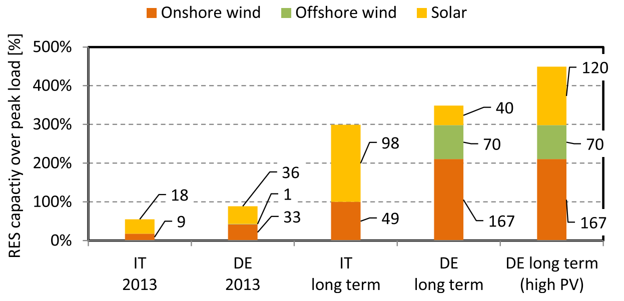
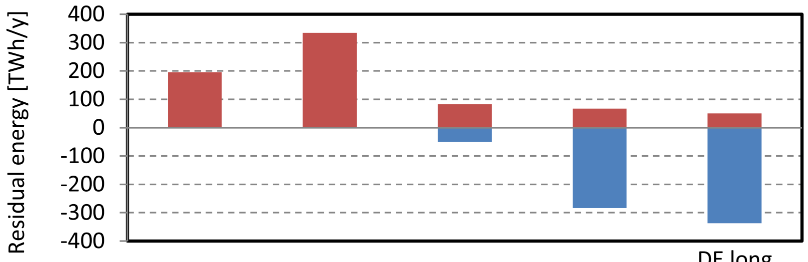


Fig. 15 – - Ratio of RES installed capacity (wind and solar) over peak load for Italy and Germany in reference case (2013) and expected long-term evolution (for Germany from Ref. [24]). Labels show absolute installed capacity (GW).

Considering the long-term evolution, the projections lead to a comparable overcapacity of RES with respect to peak load (i.e. 3–3.5 times). Nevertheless, the potential for P2G evidenced in Fig. 14 is very different, about 5.6 times higher in Germany on negative residual load basis. This outcome is justified by the different foreseen RES mix: in Germany a large share of wind is expected, while the Italian case shows a predominance of solar plants, featuring a more regular power production profile. Fig. 16 shows an example of two week profile with the share of energy production in the long-term scenario for Germany, which can be compared with the corresponding profiles in Fig. 6 for the Italian case.

While solar production is simultaneous to load peaks in the central part of the days (a situation comparable to Italy), distribution of wind peaks does not show a clear or repetitive



	IT 2013	DE 2013	IT long term	DE long term	DE long term (high PV)
H2 production [kton]	0	0	834	5561	6611
Installed EL [GW]	0	0	22	84	92
Positive residual [TWh/y]	196	334	83	67	50
Negative residual [TWh/y]	0	0	-51	-284	-337

Fig. 14 – Estimated residual energy (load), electrolysis capacity and hydrogen production in current conditions or exploiting wind and solar technical potential for Italy and Germany. An additional 'high PV' case includes a higher share of this technology [53].

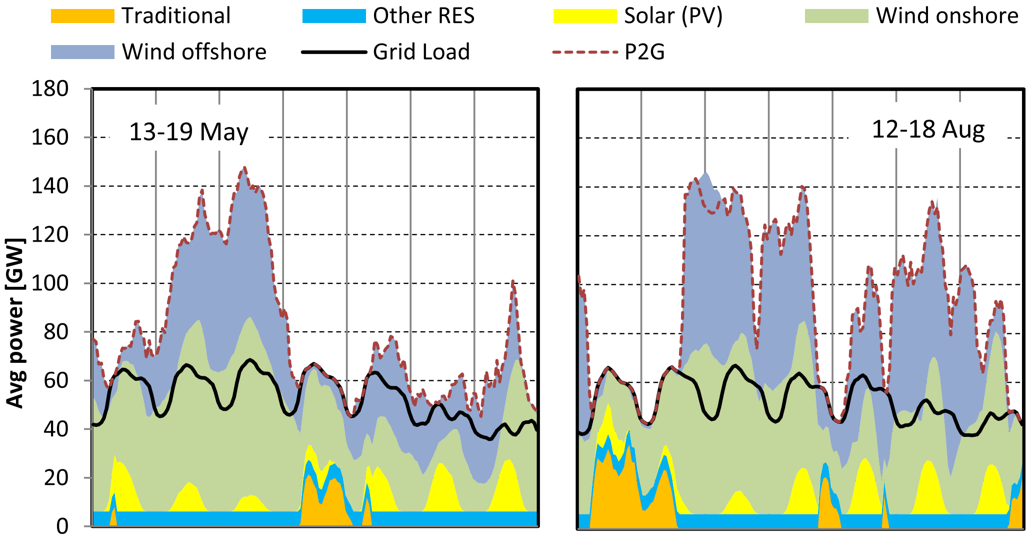


Fig. 16 – Hourly electricity production share by source and excess energy recovery. Details of weeks 13–19 May and 12–18 August capacity for German long-term cases.

pattern, with large peaks corresponding to low load periods. This last feature is strongly favorable to P2G, yielding an abundance of excess energy available for P2G conversion. Moreover, the presence of off-shore wind plants with a different pattern (i.e. long periods of constant production) amplifies the mismatch between load and production.

If a high-solar RES share scenario is applied to German production profiles, e.g. having the same solar power over peak load ratio of the Italian case, the negative residual load available for electrolysis drops from 284 to 46 TWh/year (19.5 GW of EL installed capacity, 580 kton/year of hydrogen, excess energy recovery 60%), very close to Italy's figure (51 TWh/year). On the opposite, the high-wind share scenario, when applied to Italian case, leads to negative residual load increased up to 174 TWh/year, recovered at 93.5% with a 46 GW installed EL capacity; the corresponding hydrogen production would jump to 2924 kton/year, i.e. 3.5 times higher than in the reference long-term scenario of Fig. 11.

This comparison lead to the conclusion that a RES electricity production system based on a higher solar vs. wind penetration yields advantages by the point of view of the electric system, thanks to the better correspondence with load and the regular pattern. On the other hand, larger wind shares, in particular off-shore, are more favorable to a wider deployment of P2G systems.

Summary and conclusions

The foreseen evolution of RES installed capacity in the electric power mix will lead in the future to periods where large quantities of excess electricity have to be stored or wasted. The analysis of the Italian case shows that an extension of installed RES capacity up to the foreseen technical potential (wind 49.1 GW, solar 97.6 GW) yields a relevant amount of excess energy (about 51 TWh/y) which is in principle available for electrolysis and P2G. The corresponding hydrogen production is equivalent to 5–6% of the total natural gas consumptions, while if dedicated to mobility fuel supply the fraction can increase up to 6–8% of total consumptions. The comparison with the current size of the transport system yields a relevant impact on car sector (covering about 17% of the Italian car fleet), while the public transport (buses) could be almost completely covered by hydrogen from P2G. Larger quantities could be achieved by the installation of dedicated RES plants (e.g. further repowering of onshore wind plants, addition of large off-shore plants).

The influence of several parameters used for the simulations was also investigated, in particular:

- the selected time series (i.e. reference year for electric load profiles) has little influence, so that results can be considered robust with respect to temporary conditions (i.e. weather, seasonality, ...);
- addition of "Business as usual" increase in electricity demand (instead of a substantial stability) would strongly reduce the potential for P2G systems (about halved in correspondence to a 25% increase with respect to the current load);
- wind and solar technologies have very different impacts on excess energy profiles and consequently on the amount of produced hydrogen. The two technologies taken alone yield very low negative residual load (excess energy), while their contemporary use increases the profiles mismatch;
- the operating hours of the electrolysis system, whose amount grants profitability, influence the amount of installed electrolysis capacity and the hydrogen production. At about 22 GW of installed capacity (about 13% of RES) the EL system works for 1800 equivalent operating hours, assumed as profitability threshold, and generates 834 kton/y of hydrogen production. An increase up to ~40 GW reduces EOH to 1200, but increases hydrogen production up to 1100 kton/y, with low marginal increase for higher installed P2G capacities;

- below about 70–80 GW of total RES, the 1800 EOH profitability criterion cannot be met;
- the persistence of current transmission limitations between Italian high-load zones and high-RES zones would increase up to 40% the total hydrogen production (1141 kton/y), in connection with an additional 5.7% total installed P2G capacity.

Depending on the selected case, the load percentage covered by RES is between 62 and 71%.

The comparison with the German case, which exhibits a similar ratio of installed RES capacity to peak load, evidences that a predominantly wind-based system like Germany's foreseen power mix yields a much higher availability of energy for P2G; in particular, the potential contribution of offshore wind to overall P2G hydrogen production is remarkable. Due to that, the long-term deployment of P2G systems allows larger capacities in Germany than in Italy: for instance, given the same utilization factor for electrolysis at 1800 equivalent operating hours, P2G to RES installed capacity is 41% in the German case vs. 15% in the Italian one (15%). The comparison allows to evidence that a RES electricity production system based on high solar penetration (like in the case of Italy) yields advantages from the point of view of the electric system, because of the more regular RES production pattern and better correspondence with the load profile. On the other hand, a larger wind share, in particular offshore, is favorable to increase the capacity of P2G systems.

In all the cases, it shall be highlighted that many issues have to be solved before a 100% RES electric system could be physically implemented, as the fast ramping of solar production and wind fluctuations. Available energy recovery has also to be optimized (load peak shaving). Therefore, a parallel use of traditional (e.g. fossil fuel based) technologies can be deemed necessary also in a medium-long term perspective. Hydrogen technologies and P2G would strongly help in facing the challenge.

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