# Development of benchmark scenarios for sector coupling in the Italian national energy system for 100% RES supply to power and mobility

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**Abstract.** The urgence of decarbonization has pushed many countries to set ambitious net-zero $CO_2$ emission targets by 2050. This requires a substantial transformation of energy sources, conversion methods, and final uses. This work investigates the structure of the future Italian energy system – in terms of power generation capacity, energy storage, mobility fuel shares – and assesses benchmark scenarios able to reach a fully decarbonized supply in power and transport sectors, considering their long-term evolution. The analysis adopts a multi-node multi-vector model that simulates the year-long energy system behaviour with hourly time resolution and optimizes sizing (installed capacities) and operation (energy flows). The model considers power generation from different sources, electric consumption, and mobility demand for energy vectors, focusing on electricity and hydrogen. The required installed capacities of RES power plants and energy storage systems appear to be extremely high (at least 10x today's solar PV or more), but in general positively influenced by sector integration strategies and energy vector multiplicity. Energy storage and flexibility solutions are essential, combining battery storage, Power-to-Hydrogen, Power-to-Power, smart charging, and vehicle-to-grid. If capacity installation is limited (e.g., due to land availability), the need to satisfy consumption yields significant import requirements, which also depend upon the mobility mix and the decarbonization targets.

## 1 Introduction

The pressure on decarbonizing the energy systems is increasing worldwide and it is moving into the goal of net-zero carbon dioxide ($CO_2$) emissions, as proposed in California by 2045 and in the European Union with the *Green Deal* plan by 2050. Most countries recognize the need for a substantial transformation of exploited energy sources, adopted conversion methods, and final energy uses; however, the actual achievements and the implementation of adequate measures are slow, as many studies report, such as the 'Stated Policies Scenario' by the IEA [1] or the analyses from the European Commission [2].

Given the importance to assess the planned system evolution, this work aims at developing a scenario analysis able to identify the possible structure of future energy

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systems (in terms of power generation capacity, energy storage capacity, mobility fuel shares, and sector integration options) in order to achieve a complete decarbonization (i.e., zero $CO_2$ emissions). The analysis adopts a multi-node model to simulate the national energy system year-long behaviour, with hourly time resolution and spatial aggregation according to the electric market zones, optimising the operation (energy flows distribution and energy storage uses) as well as the design (installed capacities).

The main focus is the investigation and comparison of benchmark scenarios that achieve a 100% RES energy vector supply in Italy, considering the long-term evolution of the power and transport sectors in terms of expected demand, in a conceptual framework going in the same direction of the Italian *Long-Term Strategy* (LTS) for decarbonization [3]. Energy storage, hydrogen, and green gas are essential to decouple generation and consumption, which can occur via Power-to-Hydrogen, battery storage systems, smart charging of electric vehicles, and vehicle-to-grid applications.

## 2 Methods

This study relies on a nodal model for the analysis of multi-vector and multi-sector energy systems at the regional or national scale. The model applied here is developed on the basis of previous modelling activities regarding the analysis of high-renewable electricity networks [4] and the integration of power and transport sectors [5,6].

The model simulates the year-long operation of the energy system, solving a linear programming problem that guarantees the supply-demand match of each energy vector (electricity, natural gas, hydrogen) at each node and at each time step. The possibility of storing energy vectors is exploited, according to the availability of multiple storage system types. The solution of the balance equations is performed with a perfect-foresight approach by an optimization algorithm that identifies the required installed capacities of RES generation plants and energy storage devices as well as the optimal system operation (energy flows and energy storage content variation), aiming at minimizing either the costs (economic approach) or the dependence on non-renewable sources (technical/ or environmental approach) or a combination of these. Containment of RES curtailment might also be involved. The model implements the contemporary presence of alternative options, seeking the best combination among different uses of the energy vectors. For example, in the case of hydrogen, there could be exclusive recovery of excess renewable electricity via electrolytic hydrogen production and injection into the gas grid, or hydrogen storage linked with subsequent use in hydrogen-to-power systems (power-to-power applications, P2P), as well as the need to satisfy an imposed demand such as fuel cell electric vehicles.

The system topology is represented according to the assumed spatial resolution (in this work, the six Italian electric market zones). The exchange of energy vectors is possible between nodes, under technical limitations (maximum transfer capacity), while transmission and distribution of energy vectors within each node is unconstrained (i.e., lumped or copper-plate assumption for the case of electricity exchange). For the electric and the gas grids, this is reasonable compared to real electrical networks where most constraints are in the high-voltage lines connecting market areas or in high-capacity pipelines crossing long distances. For hydrogen, this assumes that a proper delivery infrastructure will be built, possibly combining multiple transport modalities.

Figure 1 offers a schematic of the energy system representation, showing intra-nodal energy flows, interactions between technologies, and inter-nodal energy vector exchanges.

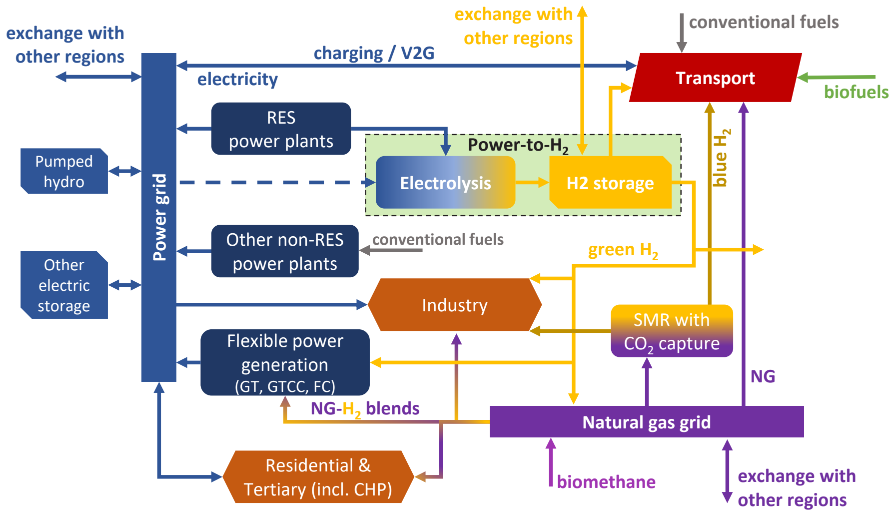

**Fig. 1.** Schematic of the energy connections within one node of the modelled energy system.

The model runs yield results that indicate the system needs. Due to the inherent simplifications, such as hourly average quantities and unconstrained intra-zonal energy exchanges of energy vectors, the results may be seen as a lower minimum boundary in terms of required installed capacities of RES generation plants and energy storage devices rather than a precise description, since actual power grid congestions and energy vector distribution limitations will impose additional constraints. The simulations aim at providing an assessment of the future Italian energy system under the ambitious target of 100% RES energy provision to the integrated power and transport sectors. The purpose is to look at the technical evolution, which involves a massive introduction of RES power generation capacities, low-emission vehicles, and sector-interwoven energy storage solutions.

It shall be also highlighted that, in addition to power and transport which are the two most important sectors in terms of energy consumption, current decarbonization targets are also addressing other $CO_2$-emitting sectors, in particular industrial processes using fossil fuels either as a feedstock or for high temperature heat generation (e.g., ammonia and methanol production, steel and cement production) as well as other hard-to-abate sectors, whose addition to the picture would further enlarge the new installation requirements.

## 2.1 Energy system balances

The power sector is modelled in terms of installed RES capacities, generation and demand time series to rescale, and electric-to-electric storage systems. The transport sector is described via an estimate of vehicle stock and shares, pushing for a larger introduction of low-emission solution fed with either electricity or hydrogen, combined with a limited presence of ICEVs that rely exclusively on biofuels (these are not investigated). In addition, all three mobility areas are taken into account (passenger cars PCs, light-duty vehicles LDVs, high-duty vehicles HDVs). Integration between the two sectors is driven by electricity and hydrogen demand from vehicles, hydrogen production from surplus electricity, Power-to-Power applications, and Vehicle-to-Grid technologies. Load electrification in other sectors (mainly buildings, where the majority of heating demand is likely to move to electricity use in heat pumps) is accounted for through the expected variation of electric consumption.

A balance equation for the electricity supply-consumption equilibrium is solved at each time step *t* for each node *z*:

$$\sum_k P_{iRES,k}(z,t) + \sum_j P_{pRES,j}(z,t) + \sum_l P_{exch,l}(z,t) + P_{GTCC}(z,t) + \sum_s P_{out,s}(z,t) + P_{FC}(z,t) + P_{V2G}(z,t) + P_{import}(z,t) = P_{load}(z,t) + \sum_s P_{in,s}(z,t) + P_{P2H}(z,t) + P_{curt}(z,t) \quad (1)$$

where $P_{iRES,k}(z,t)$ and $P_{pRES,j}(z,t)$ are the electricity generation from RES power plants exploiting intermittent source *k* and programmable technology *j*, respectively, $P_{exch,l}(z,t)$ is the electricity exchange with an adjacent node along connection *l* (positive if entering the node), $P_{GTCC}(z,t)$ is the generation from gas turbine combined cycles (assumed as the preferred conventional power plant options), $P_{FC}(z,t)$ is the output from electrochemical P2P applications via fuel cells, $P_{V2G}(z,t)$ is the release of electricity from vehicles for Vehicle-to-Grid, when available. As closure elements, $P_{import}(z,t)$ is the residual generation need, accounted for as import from abroad, while $P_{curt}(z,t)$ is the curtailment (i.e., surplus generation that exceeds the load and the absorption by storage systems).

$P_{load}(z,t)$ is the total electricity demand comprising both regular grid loads ($P_{load,grid}(z,t)$) and transport-related consumption by plug-in electric vehicle charging ($P_{toPEV}(z,t)$) as well as compression consumption in hydrogen refuelling stations ($P_{HRS}(z,t)$):

$$P_{load}(z,t) = P_{load,grid}(z,t) + P_{toPEV}(z,t) + P_{HRS}(z,t) \quad (2)$$

Many electric-to-electric storage technologies can be included, each represented by a power output $P_{out,s}(z,t)$ and a power input $P_{in,s}(z,t)$. For any storage technology *s*, the time evolution of the storage energy content in zone *z* is described by $E_s(z,t)$:

$$E_s(z,t) = E_s(z,t-1)\,(1-\varepsilon_{sd,s}) + P_{in,s}(z,t)\cdot\Delta t\cdot\eta_{in,s} - P_{out,s}(z,t)\cdot\Delta t/\eta_{out,s} \quad (3)$$

where $\varepsilon_{sd,s}$ is the self-discharge coefficient for the given time step $\Delta t$, while $\eta_{in,s}$ and $\eta_{out,s}$ are efficiencies representative of the energy losses during the charging and discharging processes, respectively.

Hydrogen production and consumption are balanced by means of a storage balance equation, written in chemical energy units, which tracks the stored amount of hydrogen in each node $Q_{H2}(z,t)$ as the difference between the content in the previous time step plus the production via electrolysis (P2H) and the consumption for power generation in fuel cells ($P_{FC}(z,t)$), the injection into the gas grid and/or towards GTCCs ($q_{H2,blend}(z,t)$), and the direct use in mobility ($D_{H2,mob}(z,t)$) or industry ($D_{H2,ind}(z,t)$):

$$Q_{H2}(z,t) = Q_{H2}(z,t-1) + P_{P2H}(z,t)\cdot\Delta t\cdot\eta_{P2H} - P_{FC}(z,t)\cdot\Delta t/\eta_{FC} - q_{H2,blend}(z,t) - D_{H2,mob}(z,t) - D_{H2,ind}(z,t) \quad (4)$$

where $D_{H2,k}(z,t)$ is the hydrogen demand from sector k (mobility or industrial applications), whereas $\eta_{P2H}$ and $\eta_{FC}$ are the efficiencies of electrolysis and fuel cell systems, respectively.

## 2.2 Simulation and optimization

The model is written using the *Matlab*® language, to favour the development of a highly-controlled tool that can be modified at need to take into account a multiplicity of scenarios, technologies, and options. A set of scripts and functions allows to first read the system features (spatial topology, time resolution, time horizon), then define the reference data (time series of iRES power generation and of electricity demand, to be rescaled according to the installed capacity and the total consumption, respectively, vehicle stock, specific consumption), and finally receive by the user the selection parameters that characterize each run (presence or absence of different energy storage technologies, assigned or variable installed capacity of solar PV and wind power generation plants, allowed use of P2P and V2G, etc.). Based on the input data and according to the selection parameters, the appropriate set of equations is implemented that represents the system behaviour, adjusting the above-described equations to the presence or absence of technologies and options. This is performed by exploiting the *Yalmip* libraries to create the linear optimization problem, which is then solved using commercial algorithms from the *Gurobi*™ solver, leading the output which includes the time series of all energy flows and the installed capacities.

The sizing problem is solved together with the simulation of system operation, which identifies the power exchanges along inter-zonal connections, the interactions with energy storage devices, and the use of electrolysers and flexible power generation resources (GT, GTCC, fuel cells), in order to maximise the overall exploitation of RES to satisfy the energy vector consumption throughout the year, under the given constraints. The objective function is a weighted sum of installation costs (PV, electrolysers, fuel cells) and of operational costs (energy vector import, inter-zonal exchange, storage use). These take into account fictitious specific costs whose importance is not the absolute values but rather the relative proportion. In particular, the import of energy vectors (electricity or hydrogen) is assigned a very high specific costs to only allow them when domestic coverage of the 100% RES request is not possible (see simulated case E). Note that the projected specific costs (€/kW$_{nom}$) of PV and electrolysers lie in a rather similar range, so limiting the total installed capacities would lead to similar results than minimizing the installation costs, and the main impact is the possibility of direct electric use (always favoured) in contrast of actual need for hydrogen fuel (e.g., mobility) or for time shift (chemical energy storage).

In addition to the balance equations, other constraints are included to guarantee that the installed capacity of electrolysis systems and flexible power generators is properly estimated. The model performs energy-based simulations that look at the technical potential for operation. To partially take into account the economic feasibility of the installations, a minimum annual capacity factors is imposed on storage and hydrogen technologies (Eqs. 5 and 6). For example, electrolysis systems and fuel cells are constrained to have 2000 and 1000 minimum equivalent operating hours, respectively. When the 100% RES share is targeted, however, at least one storage option must remain unconstrained, otherwise the solution would push for extreme over-installation of RES generation plants, resulting in massive curtailment.

$$\sum_t (P_{P2H}(z,t)\cdot\Delta t) \,/\, P_{inst,P2H}(z) \geq EOH_{min,P2H} \quad \forall z \tag{5}$$

$$\sum_t (P_{FC}(z,t)\cdot\Delta t) \,/\, P_{inst,FC}(z) \geq EOH_{min,FC} \quad \forall z \tag{6}$$

Similar constraints are implemented for electric-to-electric storage via battery energy storage systems, when their sizing is investigated. The limit is expressed in terms of equivalent operating cycles (EOC), since the capacity is more effectively expressed in terms of maximum energy stored:

$$\sum_t (P_{out,BESS}(z,t)\cdot\Delta t) \,/\, E_{inst,BESS}(z) \geq EOC_{min,BESS} \quad \forall z \tag{7}$$

The net balance of the stored quantities (either electricity in batteries, water in pumped-hydro systems, or hydrogen) is constrained to be null, so that results can be representative of one generic year in a multi-annual sequence:

$$E_s(z,t=end) = E_s(z,t=start) \quad \forall z \; \forall s \tag{8}$$

$$Q_{H2}(z,t=end) = Q_{H2}(z,t=start) \quad \forall z \tag{9}$$

# 3 Data and assumptions

The model is based on a multi-nodal and multi-sector representation of the country, taking into account the upcoming and projected sector integration technologies, such as energy storage solutions, hydrogen, smart charging of plug-in vehicles, and innovative uses of existing equipment. The analyses consider power generation and consumption, mobility demand of energy vectors, and partially the heating&cooling demand from building, via electric demand evolution.

## 3.1 Spatial resolution

The model describes Italy according to the geographical subdivision defined by the electricity TSO *Terna* for the operation and control of the power grid, which creates six zones that are also used as electric market areas by *GME*. This also allows a straightforward integration with power sector data from the same source. The subdivision is reported in Fig. 2.

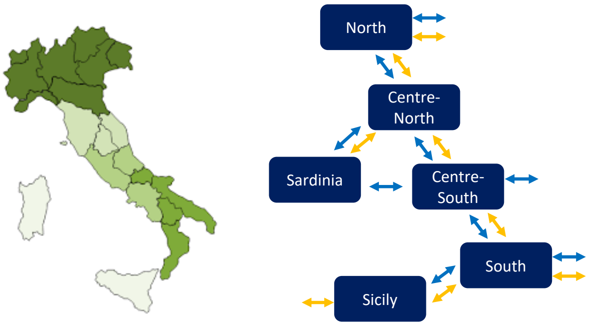

**Fig. 2.** Spatial resolution of the Italian energy system: (left) geographical map and (right) schematic of interzonal connections (blue: electricity, orange: gas/hydrogen).

The transfer of electricity between nodes is constrained by the grid topology, according to the blue connections in Fig. 2 (right). In the case of Italy, this strongly affects the national renewable share due to the elongated shape of the country and the mismatch between the location of high RES availability (mainly southern areas for both wind and solar) and of large electric load (mostly northern areas). Electric interconnection upgrade is accounted for in the studied scenarios, considering the estimates for 2040 provided by TYNDP2018 [7] according to ongoing works and planned reinforcements. Overall, these modifications represent a doubling of maximum power transfer between Sicily and the mainland and a general grid reinforcement in the order of 30-50%.

The geographical resolution is relevant also for the transport sector, since the distribution of the vehicle stock affects the location of the energy vector demand. The same clustering areas of the power sector are used, assuming that the stock proportion between zones in the scenario will remain equal to today’s status. Since today’s data show that the variation of fuel shares between the six zones is limited, these are kept homogeneous also in the scenarios.

The same resolution is considered for the transfer of other energy vectors (natural gas, hydrogen, and green gases), according to the orange connections in Fig. 2 (right). In particular, a hydrogen network is considered, connecting each zone to neighbouring zones. This might consist of pipelines (in line with today’s gas grid, which is expected to be renovated and at least partially converted to $H_2$), delivery via trucks, trains, or ships (similarly to liquid fuel distribution), or a combination of those. The zone Sardinia, which correspond to the namesake island, lacks a widespread natural gas distribution system today, as well as a natural gas link with the mainland. Taking into account the industrial expressions of interest for building such an infrastructure [8,9] as well as the assumed introduction of GTCCs and the P2H potential driven by the high RES capacity, a hydrogen connection is strategically deemed important, in the form of a transfer with zone Centre-North, without the need to specify whether this will occur via an undersea pipeline or via ship transport.

Fig. 2 also shows the import/export connections, which differ depending on the energy vector, following the existing installations of international electric lines and natural gas pipelines (assumed reconverted to hydrogen).

### 3.2 Power generation and demand

Most countries worldwide have pledged for a profound transformation of their energy systems towards sustainable ones. To comply with this commitment, their economies will need to switch to a low-carbon and high-RES energy supply. Within the EU, in particular, all countries were mandated to develop a *National Energy and Climate Plan* (NECP) and later a *Long-Term Strategy* (LTS) about the projected evolution of their energy system, with medium- and long-term estimates, subject to revisions and updates according to actual implementation and technology evolution. More recently, within the EU Green Deal, the target became the complete decarbonization by 2050 [10].

Table 1 summarises the evolution of RES power generation capacity in Italy in recent years and details the projected values for 2030 and 2050. As a comparison, estimates of the potential installation of intermittent technologies in the long term developed by the authors led to 137.2 $GW_p$ for solar photovoltaic (PV) considering available rooftop and façade surfaces with suitable availability parameters (south-facing sides, no protected building, etc.), 49.1 GW for onshore wind, and 9.5 GW for offshore wind. These values, which are in line with the LTS forecasts especially for the wind resource, were assessed combining technical and economic evaluations, as reported in [11], by reviewing estimation studies in the scientific literature [12–14] and in international agencies' reports [15–17], as well as a dedicated assessment on offshore wind potential [14].

**Table 1.** Installed capacity of RES power plants in Italy: historical data [20,21], 2030 national plan from NECP [22], and available data for 2050 from LTS [3].

| | **2010** | **2016** | **2020** | **2030*** | **2050** |
|---|---|---|---|---|---|
| Solar PV | 3.5 GW | 19.3 GW | 21.7 GW | 52.0 GW | 200-300 GW |
| On-shore wind | 5.8 GW | 9.4 GW | 10.9 GW | 18.4 GW | 40-50 GW |
| Off-shore wind | - | - | - | 0.9 GW | |
| Geothermal | 0.8 GW | 0.8 GW | 0.8 GW | 0.95 GW | uncertain |
| Renewable hydro | 17.9 GW | 18.6 GW | 19.1 GW | 19.2 GW | uncertain |
| Bioenergy | 2.4 GW | 4.1 GW | 4.1 GW | 3.8 GW | uncertain |
| Pumped hydro | 7 GW;<br>700 GWh | 7 GW;<br>700 GWh | 7 GW;<br>700 GWh | 10 GW;<br>uncertain | 17 GW;<br>uncertain |

** The 2030 national plan includes 880 MW of concentrated solar plants, but the development of this technology is uncertain and it is left out of the scope of this work.*

Limited variations in geothermal and hydroelectric installed capacities have occurred lately and big shifts are not expected by the national plans, due to the exploitation of most available resources in the country since the early discovery. On the opposite, a wide range of suggestions is found with regard to run-of-river hydropower plants in different forecast studies [7,18,19], so that the contribute of this source can be hardly predicted. An increase to 25 GW is, however, a conservative yet realistic assumption. Bioenergy-based power generation features a similar uncertain evolution due to the variety of sources as well as the competition with food harvesting and biofuel production.

Since solar PV has the most abundant potential in Italy, its installed capacity is the free variable in the analysis. Given the results of previous simulations, it is expected to find very large capacities, even above the Italian LTS estimate of 200-300 $GW_p$, especially when widening the sectors to be integrated. Within this capacity, as mentioned above, nearly 137.2 $GW_p$ are assumed feasible with rooftop installations deployed over civil and industrial roofs [23], while all the additional capacity requires ground-based or other types of PV installations. In addition to that, if the Italian actual potential should be saturated, it can be considered that additional PV capacity could be installed abroad, e.g., in North Africa or other nearby countries, and directly linked to help sustain Italy's (and in perspective EU's) power and hydrogen needs with a combination of power lines and gas pipelines [24]. To reduce complexity and given the available long-term projections for onshore and offshore wind, resource competition is avoided in the model and the wind installed capacity is fixed (onshore 49.1 GW, offshore 9.5 GW). The installed capacities of other RES are set equal to the most recent projections, taking into account the above considerations. For geothermal power plants, it is assumed to reach 1.0 GW as upper limit due to the limited suitable areas. Hydroelectric plant nominal power output is assumed to increase to 25.0 GW, in line with the estimated generation increase proposed by [25]. For pumped hydropower storage systems, this work assumes to keep today's installed power and energy capacities (about 7 GW and 700 GWh country-wide), since the projections only provide a power capacity value and do not offer location details. Waste-to-energy is also included in the model, and it is associated with RES plants under the highest priority of use, because the disposal of waste through incinerators (at least for a given fraction of waste) is considered a non-optional accomplishment to be guaranteed. Values are obtained from governmental regulations [26] and a constant flat generation profile is considered, taking into account the average LHV of waste (10 MJ/kg) and efficiency of the steam cycle-based plants (25% LHV-to-electric). Note that this is a small contribution to the country load, in the order of 1.5% of the 'regular' consumption (i.e., excluding mobility demand). Bioenergy plants, thanks to the intrinsic dispatchability, act as a fully flexible power generation option, with a cumulative installed capacity of 4 GW, and help managing the residual load together with energy storage devices and P2P units, before GTCCs or import contributions are called in. Bioenergy use is also constrained in terms of annual electricity output, to take into account limitations in fuel supply and competition with other uses, setting such limit to the 2018 output [20]. The model considers the exploitation of gas turbine-based power plants through hydrogen feeding, considering a revamping of the existing 24 GW capacity in the form of GTCCs featuring an average 60% efficiency, plus 1 GW installation in zone Sardinia, where existing coal plants are being shut down and reconversion is under consideration. In case of model runs with an imposed RES share target below 100%, NG fuelling is possible, and the model assumes full flexibility of GTCC in terms of NG-H2 blend input as targeted by latest generation gas turbines.

A review of allocation approaches for the distribution of RES installed capacity among the six zones proved that alternative distribution methods do not lead to significantly different proportions from today's situation, even when combining relevant parameters (e.g., resource availability, land area, built area for rooftop solar) [5]. Therefore, the distribution in the future scenario is kept proportional to the present one [20], except for a minor adaptation in solar PV location that better accounts for the higher average radiation in southern areas (many installation occurred in northern areas due to both larger land and rooftop surface areas, but also because the economic momentum was stronger).

Regarding electricity consumption, besides plug-in mobility that is treated separately (see Section 3. 3), the total annual demand is assumed to increase by 12% with respect to recent years, in which it was stable around 320 $TWh_{el}$/y [20], in accordance with the LTS perspective [3], considering the combination of additional loads due to electrification (e.g., heating and cooking devices) and energy efficiency measures on existing equipment. The year-long hourly profile is assumed unchanged (2018 data), for simplicity.

## 3.3 Road mobility

### *3.3.1 Current status and projections*

Today, the road mobility sector is dominated by the use of oil-based fuels (petrol and diesel) in internal combustion engine vehicles (ICEVs), both in Italy and worldwide. Biofuels such as bioethanol and biodiesel are increasingly supported by the regulation, e.g., the EU already mandated 10% biofuels blending with conventional fossil fuels by 2020 [27], but they are impacted by costs and resource availability. Among ICEVs, Italy represents a unique case of wide diffusion of natural gas (NG) vehicles (currently used in more than a million passenger cars) as well as liquified petroleum gas (LPG) ones, which provide some environmental advantages, yet they still run for the majority on fossil fuels. Biomethane use has been already mandated to reach 20% in mobility, where it is subsidized as natural gas replacement, thanks to the biogenic origin that makes the $CO_2$ emissions climate-neutral.

The introduction of plug-in electric vehicles (PEVs) is surging in terms of sales, but they still constitute a small share of the stock. The PEV category includes (i) battery electric vehicles (BEVs) that run solely on an electric motor fed from an onboard battery and (ii) plug-in hybrid electric vehicles (PHEVs) equipped with a hybrid propulsion system comprising an internal combustion engine (ICE), a liquid fuel tank, an electric motor, and a battery that can be charged both during motion (from ICE and/or regenerative braking) and via an external electric connection; with several possible configurations where the wheels are mechanically driven by the electric motors and/or the ICE. Fuel cell electric vehicles (FCEVs) use hydrogen stored in an onboard tank as feedstock, which is electrochemically converted into electricity to drive an electric motor, with the addition of a small battery that manages peaks during acceleration and allows regenerative braking. FCEVs are counted in tens of thousands globally among passenger cars, with the market concentrated in California, Japan, and Germany, whereas recent momentum has been registered for bus and truck applications (e.g., in Japan and China). Applications in Italy are currently limited to South Tyrol, where the only public refuelling station is installed, while a few cities have implemented hydrogen-fuelled FCEVs among buses for public transport and a new national plan is addressing the installation of some tens of refuelling stations within the mid-term.

Looking at future mobility scenarios regarding passenger cars, available studies in the scientific literature often introduce arbitrary assumptions (e.g., 10%, 50%, or even up to a drastic and unlikely 100% BEV share) [28] or develop parametric analyses of the long-term evolution assessing the effects of different BEV/PHEV/FCEV shares [29]. Utilities are also interested in the topic, due to their role in providing the electricity during the charging events. A recent study commissioned by Enel SpA (the main Italian electric utility) suggested a large and quick penetration of PEVs in Italy, proposing different scenarios with a combined quantity of BEVs and PHEVs between 3 and 9 million in 2030 [30]. The IEA stated policies scenario sees a 30% share of electric vehicles in 2040 in advanced-economy countries [31].

Among the few evolution studies that proposed a more detailed assessment of the passenger car stock, two are reported in Table 2, in terms of vehicle type/fuel shares and total stock, also compared to today's status (2016 data [32]). The IEA 'ETP 2DS high H2' scenario [33] foresees a slight decrement in the total fleet and a combined presence of BEVs, PHEVs, and FCEVs, surging after 2030. The 'EU Reference Scenario 2016' estimate [34] is a projection of ongoing policies rather than a forecast of evolution and is far more cautious, so that low-emission vehicles do not exceed 15% of the stock.

**Table 2.** Passenger car stock and fuel shares in Italy: current status and scenarios.

| | | **2020** | **EU Ref. Scenario 2016** | | **IEA ETP 2DS high-H2** | |
|---|---|---|---|---|---|---|
| | | | **2030** | **2050** | **2030** | **2050** |
| Share [%] | ICEV* petrol | 46.8 | 33.5 | 30.1 | 50.4 | 23.0 |
| | ICEV* diesel | 43.9 | 47.0 | 40.6 | 30.2 | 9.6 |
| | ICEV LPG/NG | 9.2 | 15.7 | 16.4 | 4.3 | 3.0 |
| | PHEV petrol | <0.2% | 1.4 | 3.9 | 5.0 | 11.9 |
| | PHEV diesel | | 1.2 | 2.4 | 4.3 | 7.4 |
| | BEV | | 1.0 | 4.9 | 3.6 | 14.8 |
| | FCEV | - | 0.2 | 1.7 | 2.2 | 30.3 |
| Total stock | | 40 million | 39 million | 42 million | 37 million | 36 million |

* *Hybrid electric vehicles (HEVs) that feature a dual propulsion by ICE and electric motor without an external electric connection for charging are not separated and counted as part of the ICEV group.*

The categories of light- and medium-duty vehicles (LDVs and MDVs, simply LDVs in the following) comprise a broad variety of solutions, with different functions, requirements, and payloads (from freight transport to construction vehicles, from recreational mobility to emergency service). Today, they mainly adopt ICEs as drivetrain and are fuelled by petrol or diesel fuel. Low-emission options are available or under development (biofuels, hydrogen, battery), but there is no apparent prevalence of one option for the long-term evolution, given the varied applications, the general need for reliability, and in some cases the need to operate according to non-ordinary patterns (emergency vehicles) or in unusual environments (recreational vehicles, off-road and construction vehicles).

The last road mobility segment is related to heavy-load or freight transport by trucks (heavy-duty vehicles, HDVs). Forecasts in this context are scarce, due to the current almost complete reliance on diesel-fuelled ICEVs and the absence of economically viable alternatives, in a sector where total cost of ownership is the main selection parameter. Recently, the introduction of LNG-based natural gas ICEVs among road tractors have shown a rapid growth – from 30 to 2000 units per year between 2015 and 2018 in Italy [35]. Available studies often assume round numbers to assess possible effects of new and cleaner powertrain technologies. In the field of HDVs, the payload is essential and this limits the suitability of BEVs [36]. On the opposite, the development of FCEVs is raising interest thanks to low tailpipe emissions, which the EU has applied in recent regulations as the environmental performance parameter. A number of subsidized projects is under development, e.g., Toyota trucks at the Port of Long Beach, Hyundai trucks in Switzerland, vehicles from Nikola in USA and in Europe through partnership with CNH Industrial.

This study does not investigate public transport (buses) nor other mobility modes (e.g., air or maritime transport), whereas the electricity consumption for trains along electrified railway lines as well as for subway units and trolleybuses is included in the electric load.

### *3.3.2 Scenario*

The definition of a long-term scenario of vehicle stocks and fuel shares require a number of assumptions. In this work, the evolution of the Italian mobility sector is described according to the following fleet variations:

- the passenger car stock decreases slightly (from today's 39 million to 36 million vehicles) and features a radical modification of fuel shares (35% ICEV, 35% BEV, 30% FCEV), based on a revision of the IEA 'ETP 2DS high H2' scenario that simplifies the shares by aggregating the HEV and PHEV categories into ICEV and BEV, respectively [33];
- the stock of light- and medium-duty vehicles is set stable at today's amount (nearly 4.5 million, considering all vehicles below 14 t), with a shift towards a homogeneous even combination of ICEV, BEV, and FCEV technologies (33.3% each);
- heavy-duty trucks (above 14 t) do not include any BEV option, in line with existing projections that identify payload reduction and stop due to recharging times as main drawbacks [37], and the stock of 670,000 vehicles [32] is assumed to be split evenly between new-generation ICEV (50%) and FCEV (50%).

The vehicle stocks are distributed among the six zones (see Section 3.1) according to the current distribution, kept unchanged for simplicity; the shares are presented in Table 3.

**Table 3.** Zonal distribution of vehicles.

| | **Passenger cars** | **LDVs and HDVs** |
|---|---|---|
| North | 46.0 % | 51.6 % |
| Centre-North | 10.8 % | 10.7 % |
| Centre-South | 21.2 % | 16.4 % |
| South | 10.8 % | 10.4 % |
| Sicily | 8.5 % | 7.9 % |
| Sardinia | 2.7 % | 3.0 % |

The average mileage of passenger cars is assumed equal to the mean between the estimates for petrol and diesel cars (nearly 11,000 km/y, according to projections from the Italian trade association *Unione Petrolifera* [32,38]). Long-term estimates of specific consumption are considered [6,38]:

- ICEV: 19.8 km/l and 22.4 km/l for petrol and diesel, respectively (density: 755 g/l and 832 g/l, respectively; LHV: 43.4 MJ/kg and 42.6 MJ/kg, respectively);
- BEV: 12.5 $kWh_{el}$/100 km [39] (significantly lower than today's average that reaches 18-20 $kWh_{el}$/100 km [40,41]);
- FCEV: 0.65 $kg_{H2}$/100 km [42], which is even an overestimation compared to very recent long-run test [43].

The categories of LDVs and MDVs comprise different vehicles in terms of functions and requirements. The average mileage is assumed equal to 40,000 km per year in both groups. The average fuel consumption of FCEVs is set equal to 3.0 $kg_{H2}$ per 100 km, whereas BEVs are assumed to feature a specific consumption of either 31.25 $kWh_{el}$ per 100 km (< 3.5 t) or 62.5 $kWh_{el}$ per 100 km (above 3.5 t) [44,45].

According to the available statistics and studies [36,37], as well as manufacturers' information, the mileage of HDVs is set equal to 100,000 km per year. In the case of heavy-duty FCEV, the specific consumption is assumed equal to 7.5 $kg_{H2}$ per 100 km, which lies in the lower predicted range [46,47] (for comparison, today's ICE-based HDVs consume nearly 30 litres of diesel per 100 km, where the energy content ratio of the two fuels is 0.32 $\mathrm{kWh}_{\mathrm{lt\ Diesel}}$ / $\mathrm{kWh}_{\mathrm{kg\ H2}}$ based on the lower heating value).

The hydrogen demand for mobility is assumed distributed uniformly throughout the year, since FCEVs are refilled at refuelling stations in a similar way to conventional transport fuels and there is no need to specify in detail the hourly station operating schedule, which relies on local storage units that are managed by the single operators. On the contrary, BEVs are charged by means of a direct connection to the electric grid, thus making it very relevant to distribute the annual demand – computed from stock, average mileage, and specific consumption – into a plausible time series. For passenger cars, this is described here as a day-long profile with two daily peaks [48]. For trucks, a night-only charging requirement is implemented, assuming that these kinds of vehicles are exploited mostly for job purposes and thus are in motion during the day.

The focus of the analysis is on electricity-hydrogen integration within the sector coupling energy system evolution; hence, ICEV fuelling schedule is not detailed and the renewable shares that are computed to feed this type of vehicles do not take into account that actual fraction of oil-based fuels, biofuels, natural gas, or biomethane use, assuming that the supply will switch to a progressive mix of sustainable options. Further work in this context is foreseen by the authors in future investigations.

### *3.3.3 Smart charging and vehicle-to-grid*

The analysis takes into account the adoption of smart charging techniques and the introduction of Vehicle-to-Grid (V2G) technologies, thus allowing to reduce the impact of PEV charging on the electric infrastructure as well as to act as a massive and distributed electric storage option. This is done by removing the imposed two-daily-peak electricity demand and adding a balance equation in the model that tracks the zonal-aggregated PEV energy content $E_{PEV}(z,t)$ in each zone $z$ at each time step $t$ according to the flexible input ($P_{toPEV}(z,t)$), the electricity consumption for vehicle propulsion $E_{road,PEV}(z,t)$, and the output towards the electric grid ($P_{V2G}(z,t)$):

$$E_{PEV}(z,t) = E_{PEV}(z,t\text{-}1)\cdot(1\text{-}\varepsilon_{sd}) + P_{toPEV}(z,t)\cdot\Delta t\cdot\eta_{ch} - E_{road,PEV}(z,t) - P_{V2G}(z,t)\cdot\Delta t/\eta_{dis} \quad (10)$$

where $\eta_{ch}$ and $\eta_{dis}$ represent the efficiencies during charging and discharging, respectively, due to heating and equipment losses. In case of smart charging without V2G possibility, the term $P_{V2G}(z,t)$ is identically null, and Eq. 10 holds as an energy storage balance for flexible charging.

The model considers V2G implementation only by BEVs in the passenger car section, assuming that LDVs and trucks have longer travelling times and larger batteries that already require longer charging times (concentrated at night time), and are therefore less likely to offer this type of service. Passenger car BEVs are assumed to have an onboard 50 kWh battery on average, with a minimum energy content of 30% at all moments. In order to limit the degradation impact on BEV batteries, the electricity input during charging and release during V2G are constrained to guarantee operation at the nominal discharge C-rate or below. This is assumed equal to 0.5C (corresponding to an energy-to-power ratio of 2 h) during charging and 0.2C (corresponding to an energy-to-power ratio of 5 h) during discharge, according to most recent BEV Li-ion battery datasheets. In order to define the energy consumption $E_{road,PEV}(z,t)$ and the available vehicle battery capacity throughout the day, a mobility use profile for passenger cars is introduced. To do so, the fraction of moving vehicles is defined, which varies during the day, according to two periods of high traffic (10% of vehicles are in motion from 7 am to 10 am and from 5 pm to 8 pm, for a total of 6 h per day), whereas a tinier fraction (2%) of vehicles is moving at other times of the day. The fractions of moving vehicles within each of these sections of the day are computed in order to guarantee the total annual mileage and assuming an average travel speed of 30 km/h, which corresponds to nearly 400 equivalent hours of use per year. The profile values are limited to two for simplicity and, for the same reason, the daily profile is repeated identically throughout the year, without differentiating Sundays or vacation periods. The resulting time series is shown in Fig. 3.

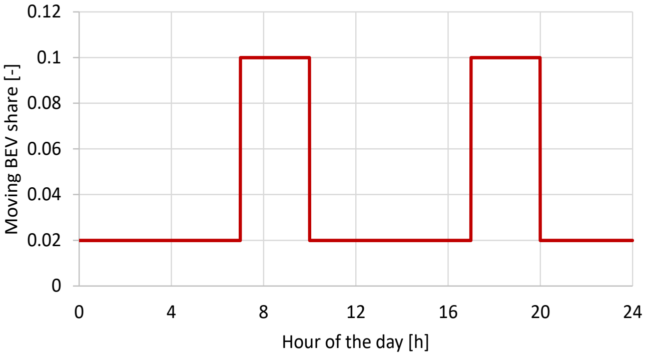

**Fig. 3.** Day-long hourly pattern of passenger car use.

Further assumptions are introduced to describe the share of non-moving BEVs that are connected to the grid (50%, an assumption meaning that half of all the parking slots used by BEV, wherever they are, are provided with a grid connection) and the fraction of these grid-connected vehicles that are available for V2G (50%). Given the spatial resolution adopted for the model, the quantities are lumped values within each zone, so that an averaging effect exists. Hence, the maximum energy capacity available for V2G at a country scale is either 28 or 31 $GWh_{el}$ in each hour, depending on the mobility profile. This work assumes that the intra-zonal electric grid is able to manage such flows, although that would likely not be the case today; the corresponding upgrade investment cost in all the country medium-voltage and low-voltage distribution grid infrastructure is not accounted for in the results. The hourly analysis does aim at evaluating the possible use of short-time peak power operation in the range of seconds or minutes.

The applied modelling approach implicitly contains the assumption of uniform distribution of the energy content among BEVs within one zone. Future steps will look at improved statistical-based assumptions for the assessment of vehicle switch between different conditions (moving, non-moving, connected, V2G-available).

### 3.3 Electric energy storage

Electricity storage using pumped-hydro facilities considers the current installed capacities (nominal power rating in pumping and generation modes, available storage capacity), which have not seen significant increases in the past decade. The plans proposed by NEPC and LTS foresee an increase in power capacity, but this is neglected here since they do not assess the actual location of these installations nor they clarify the energy capacity variation.

Market trends and projections foresee instead a wide diffusion of grid-connected battery energy storage systems (BESS), especially in combination with intermittent RES power plants, obtaining hybrid systems. To avoid adding the BESS capacity as a further variable, which would require a complete techno-economic analysis in order to identify the cost-optimal solution in competition with hydrogen systems and other flexibility options, the present analysis assumes that all projected rooftop PV plants (accounting for 137.2 $GW_p$ as explained in section 3.2) are integrated PV-BESS systems with an energy-to-power ratio equal to 4 h (nominal operation at 0.25C in both charge and discharge), given the proto-commercial status of these solutions. This assumption is very strong and implies the installation of nearly 550 GWh of battery capacity, an amount that could be feasible only with significant improvements in the economics with respect to today's situation where the battery costs are ranging between 300-400 €/kWh [49]. At a prospective capital cost of 100 €/kWh, such installation still yields an initial investment cost of nearly 55 billion €. Despite this, the inclusion of a massive portion of BESS allows to better estimate the importance of P2H systems.

### 3.4 Hydrogen systems

A key element of the investigated scenarios is the presence of hydrogen and electrochemical devices (electrolysers and fuel cells), which connect different energy sectors, decoupling clean power generation from energy vector demand for mobility, as well as acting as energy storage for later reconversion into electricity. The model finds the capacity of electrolysers for the Power-Hydrogen (P2H) conversion and of fuel cell systems (FC) for the Hydrogen-to-Power (H2P) conversion in Power-to-Power (P2P) applications. These units typically feature a fast load variation that is solved within the 1-hour time step of the model. Electrochemical devices have a stable – if not higher – efficiency when operating at partial load. The model sets constant efficiency values in line with ongoing developments of low-temperature devices, which are at early commercial maturity today:

- electrolysis devices are assumed to operate with an electric-to-$LHV_{H2}$ system efficiency equal to 65% [50,51];
- fuel cell system efficiency ($LHV_{H2}$-to-electric) is set at 50% as from medium-term projections [52,53].

The values are conservative if compared with the long-term perspective of adopting high-temperature electrochemical cells like the solid oxide cells, which are under development for both fuel cell (also available at proto-commercial stage) and electrolysis application, or even for reversible operation. Solid oxide cells, depending upon the operating conditions, can reach electric efficiency values above 60% in power generation mode and close to 100% in hydrogen production mode (electric efficiency above 100% is also possible if reaction conditions are endothermic).

The operation of fuel cells is in competition with GTCC use as flexible power generation resources (both acting as P2P options by using hydrogen). In the investigated 100% RES vision, GTCC plants are exclusively fed with hydrogen, although actual evolution is likely to involve biomethane and other clean gaseous fuels as well, e.g., syngas from biomass gasification. However, these are not detailed here as GTCC feeds because (i) they also fall under the bioenergy category and (ii) they are partially in competition with transport uses (e.g., vehicles and aircrafts) or industrial applications. The model assume a constant 60% fuel-to-electricity conversion efficiency for GTCCs, which is in line with modern GTCC plant designs predicting operation in the range of 62-64% efficiency [54], although the value will remain sensitive to partial load (whose effects are here neglected in order to keep the model linear).

Hydrogen storage is assumed available in underground form (e.g., natural or artificial caverns, depleted gas reservoirs, or other underground storage solutions) and assessed the required capacity is assessed. Possible hydrogen losses from storage facilities is neglected since both the studies on Lined Rock Caverns [55] and the preliminary measures from existing underground facilities in salt caverns have shown extremely low leakage rates [56].

# 4 Results and discussion

The model solves the balances of the national energy system, finding the values of the energy flows at each time step (hourly resolution), while determining the minimum required installed capacity of solar PV power plants and of hydrogen-related units (electrolysis systems, fuel cell systems, storage). The constraints involve the correct closure of the balances (the allowed error is set in the order of $kWh_{el}$ on the hourly zonal balances) and the 100% RES share on both power and hydrogen supply. The latter imposes that the installed renewable power plants must provide enough electricity to 'regular' loads, to plug-in vehicles, and to electric energy storage systems, as well as to electrolysers that produce the required hydrogen for the mobility demand and for P2P (via FC or GTCC). A minimum capacity factor is imposed on the operation of electrolysis systems (2000 equivalent operating hours per year) and fuel cell systems (1000 equivalent operating hours per year) to take into account reasonable economic limitations to the installed capacities. Moreover, the installed capacities of solar PV are constrained to maintain a proportion among the zones close to the revised distribution according to resource availability, land area, and built area, with a maximum deviation of ±20%. This forces the solution to consider a realistic geographical development of the installations, which are not expected to be concentrated close to the demand points and therefore will involve larger energy exchanges across the country.

The transport sector full decarbonization considers the electricity- and hydrogen-based vehicles. The remaining ICEVs among the various mobility segments is assumed to shift towards biofuels in order to reach carbon neutrality, as discussed in Section 3.2. The production of other synthetic fuels, generated from renewable electricity and hydrogen (e-fuels) would further affect the balances and is therefore left to future assessments.

The demand for the two energy vectors (electricity and hydrogen) is summarized in Table 4 by sector.

**Table 4.** Summary of energy vectors demand.

| | | |
|---|---|---|
| Electricity demand [$TWh_{el}/y$] | Regular | 352.6 |
| | Mobility | 38.1 |
| | Total | 384.2 |
| $H_2$ demand by FCEVs [$kt_{H2}/y$] | Passenger cars | 737.1 |
| | LDVs | 1482.0 |
| | MDVs | 293.8 |
| | HDVs | 2527.5 |
| | Total | 4342.5 |

The simulations are performed in four different cases that differ by the flexibility level in the transport sector and by the number of allowed P2P options (FC vs. GTCC):

A. plug-in vehicles among passenger cars are forced to charge according to a given profile, reflecting inflexible owners' behaviour with a two-peak daily profile;
B. smart charging of PEV passenger cars is allowed, distributing the charging events according to the overall system needs;
C. plug-in vehicles among passenger cars can be charged flexibly and they are also able to provide V2G service, according to the approach described in Section 3.2;
D. the use of hydrogen is possible only in FCs as P2P systems, in the vision of a hypothetical fully decentralized electricity system in which GTCCs are completely removed;

E. the installed capacity of PV systems has a cap equal to 230 GW$_p$, equal and in line with the estimate proposed by the LTS.

In the simulations, GTCCs can only operate with hydrogen, since the constraint of 100% RES share leaves any natural gas supply out of the picture, and biomethane is not detailed because it is assumed already applied in ICEVs and partially as a fraction of the bioenergy term.

The resulting installed capacities and energy balance terms are summarised in Table 5, at the country scale. In general, the values of installed capacities are massive, in lines with the very large request of energy vectors. The use of GTCCs as P2P option is preferred to the introduction of fuel cell systems, since their capacity is already available and their LHV-to-electric efficiency is higher. Therefore, results involve first a saturation of the GTCC capacity and then the addition of some FC plants to fulfil the balance. At any rate, the actual choice between the two options will be driven by investment cost for the revamping (here neglected) or installation as well as by the provided ramp flexibility during operation and by grid limitations in the areas of installation. In case E, since the installation of renewable power generation in the country is constrained, to attain the 100% RES target a large amount of import is necessary, which corresponds to more than 50% of the electric consumption. Import of hydrogen or electricity is highly dependent on assumed import and inter-zonal exchange costs.

**Table 5.** Installed capacities and energy vector quantities country-wide in the 5 analysed cases.

| | | ***A*** | ***B*** | ***C*** | ***D*** | ***E*** |
|---|---|---|---|---|---|---|
| **Passenger cars** | **Smart charging** | **No** | **yes** | **yes** | **yes** | **yes** |
| | **V2G** | **No** | **no** | **yes** | **yes** | **yes** |
| **GTCC** (@ current 25 GW capacity) | | **Yes** | **yes** | **yes** | **no** | **yes** |
| **Max PV capacity [GWp]** | | **-** | **-** | **-** | **-** | **230** |
| PV capacity [GW$_p$] | | 523.9 | 509.7 | 505.4 | 513.0 | 230.0 |
| Electrolysis system capacity [GW$_{el}$] | | 126.9 | 119.6 | 101.2 | 103.0 | 120.0 |
| Fuel cell system capacity [GW$_{el}$] | | 4.5 | 3.9 | 3.9 | 12.2 | 0.0 |
| Hydrogen storage capacity [kt$_{H2}$] | | 1994.5 | 1944.9 | 1897.9 | 1979.7 | 117.5 |
| After direct RES, before electric storage | Residual load [TWh$_{el}$/y] | 142.0 | 134.7 | 159.2 | 159.2 | 205.9 |
| | Surplus electricity [TWh$_{el}$/y] | 517.3 | 493.7 | 514.2 | 519.4 | 263.8 |
| After direct RES and electric storage, before P2H/P2P | Residual load [TWh$_{el}$/y] | 26.5 | 23.4 | 20.0 | 17.9 | 205.4 |
| | Surplus electricity [TWh$_{el}$/y] | 357.2 | 339.2 | 321.0 | 322.5 | 263.0 |
| Curtailed RES generation [TWh$_{el}$/y] | | 19.1 | 10.1 | 0.8 | 0.9 | 0.0 |
| GTCC power generation [TWh$_{el}$/y] | | 21.2 | 19.3 | 16.1 | - | 0.0 |
| Fuel cell power generation [TWh$_{el}$/y] | | 5.3 | 4.1 | 3.9 | 17.9 | 0.0 |
| Electricity import [TWh$_{el}$/y] | | 0.0 | 0.0 | 0.0 | 0.0 | 205.4 |
| Electricity to P2H [TWh$_{el}$/y] | | 338.1 | 329.2 | 320.2 | 321.5 | 263.0 |
| Hydrogen production via P2H [kt$_{H2}$/y] | | 6593.5 | 6418.9 | 6243.7 | 6268.6 | 5128.6 |
| Hydrogen import [kt$_{H2}$/y] | | - | - | - | - | 0.4 |
| Hydrogen use by GTCCs [kt$_{H2}$/y] | | 35.3 | 32.1 | 26.8 | - | 0.0 |
| Hydrogen use by FCs [kt$_{H2}$/y] | | 10.6 | 8.3 | 7.8 | 35.9 | 0.0 |

The estimated nominal capacities divided by zone are summarised in Table 6 for case C, which is selected as exemplary given the lower amount of RES and plant capacities required while favouring the domestic coverage of demand. The large presence of solar PV capacity in northern areas is not in conflict with the higher resource potential in southern areas, but consistent with the much larger land surface area available (as discussed above, the proportion of installed capacities among zones is kept in the range of ±20% with respect to the revised distribution estimate seen in Section 3.2). The significant electric demand and mobility request for energy vectors in zone North leads to significant installed capacities also of P2H and FC systems in that same zone, reducing the impact of interconnection losses. The proportions are similar in the other cases, taking into account the absence of some options, e.g., null V2G in cases A and B or replacement of GTCC operation by FCs in case D.

**Table 6.** Installed capacities of solar PV generation, electrochemical systems, and BESS, by zone.

| | **PV** **[GW$_p$]** | **Electrolysis systems** **[GW$_{el,nom}$]** | **Fuel cell systems** **[GW$_{el,nom}$]** | **Hydrogen storage** **[kt$_{H2}$]** |
|---|---|---|---|---|
| North | 219.05 | 25.24 | 3.92 | 1756.63 |
| Centre-North | 53.37 | 8.56 | 0.00 | 39.03 |
| Centre-South | 56.78 | 7.10 | 0.00 | 81.37 |
| South | 106.11 | 39.23 | 0.00 | 6.60 |
| Sicily | 38.20 | 10.49 | 0.00 | 13.54 |
| Sardinia | 31.88 | 10.60 | 0.00 | 0.69 |
| Italy | 505.39 | 101.22 | 3.92 | 1897.87 |

Looking at the energy flows on a zonal basis, the discrepancies between northern and southern areas are, once again, evident. Table 7 reports the electricity balance quantities, by zone. The results are reported in a graphical way in Fig. 4, where the 'Exchange' term involves the import of clean electricity from adjacent zones. The contribute by battery energy storage systems, either stationary or V2G, is significant (nearly 15% of electric generation country-wide), showing the importance of flexible solutions, whereas the role played by hydrogen in a multi-vector vision is constrained to 2% due to the already high need for hydrogen from mobility. However, zonal data show higher needs and different shares in some cases. In the proposed scenarios, the higher power generation in southern areas combined with the much larger electricity demand in zone North, make the latter a sink for all energy vectors and therefore it is the only zone where GTCCs come into use. On the opposite, southern zones where RES generation profiles are more favourable become exporters. On the one hand, the assigned increase of wind power capacity is entirely in southern regions. On the other hand, the PV installations resulting from the model are constrained to maintain a proportion between the zones so that an excessive increase in zone North is not favoured since it would require a corresponding increment in the other zones with cost increase with limited overall impact, so that algorithm opts to increment hydrogen production and exploit it for re-electrification. Obviously, a more detailed analysis of intra-zonal transfer limitations, ramp constraints, and electric-to-electric energy storage boundaries is likely to re-introduce a need for flexible fuel-based power plants in all zones, also in view of a partial use of other clean fuels, but this effect is not visible by the type of analysis presented here.

**Table 7.** Shares of electricity generation by zone and absolute values at the country scale, in case C.

| | **RES** | **WTE** | **Bioenergy** | **PHS** | **BESS** | **V2G** | **P2P** | | **Net import[a]** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **FC** | **GTCC** | |
| North [%] | 70.3 | 0.8 | 2.7 | 2.1 | 12.5 | 3.6 | 1.1 | 4.3 | 2.7 |
| Centre-North [%] | 70.9 | 0.6 | 1.0 | 0.0 | 16.4 | 0.9 | 0.0 | 0.0 | 10.2 |
| Centre-South [ %] | 73.1 | 1.1 | 1.1 | 2.1 | 12.8 | 1.7 | 0.0 | 0.0 | 8.0 |
| South [%] | 88.7 | 0.2 | 1.3 | 0.0 | 7.6 | 0.9 | 0.0 | 0.0 | 1.3 |
| Sicily [%] | 86.3 | 0.6 | 0.3 | 1.0 | 10.6 | 0.4 | 0.0 | 0.0 | 0.9 |
| Sardinia [%] | 87.3 | 0.3 | 1.0 | 0.6 | 9.4 | 0.2 | 0.0 | 0.0 | 1.2 |
| Italy [%] | 80.3 | 0.6 | 1.8 | 1.3 | 11.8 | 2.0 | 0.4 | 1.7 | - |
| Italy [TWh$_{el}$] | 740.9 | 5.8 | 16.3 | 11.6 | 108.9 | 18.7 | 3.9 | 16.1 | - |

[a] *Positive if inlet*

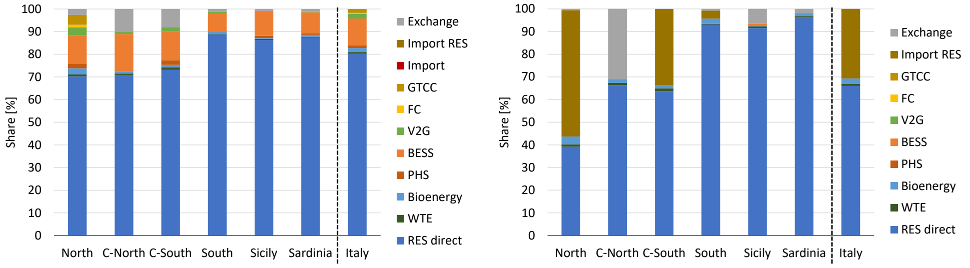

**Fig. 4.** Source shares on electricity generation in cases C and E.

In Table 9, the zonal hydrogen balance is depicted. To minimize transport losses and installed capacities, the model tries to install P2H close to the demand areas. GTCC use is favoured over FCs due to the higher LHV-to-electric efficiency (assumptions considered a long-term value of 60% for GTCCs and a moderate 50% for FCs) as well as thanks to the beneficial use of already installed capacity with respect to new installations.

**Table 9.** Zonal balance of hydrogen production and use, in case C.

| | Mobility demand [$kt_{H2}$/y] | Electrolysis | | Fuel cells | | GTCCs | | Net exchange[a] [$kt_{H2}$/y] |
|---|---|---|---|---|---|---|---|---|
| | | EOH [h/y] | Production [$kt_{H2}$/y] | EOH [h/y] | Use [$kt_{H2}$/y] | EOH [h/y] | Use [$kt_{H2}$/y] | |
| North | 2559.8 | 2180 | 1072.9 | 1000 | 235.0 | 1886 | 804.0 | 2525.9 |
| Centre-North | 538.9 | 2671 | 445.6 | - | 0.0 | - | 0.0 | 2654.5 |
| Centre-South | 862.1 | 3136 | 434.4 | - | 0.0 | - | 0.0 | 2410.2 |
| South | 527.5 | 3425 | 2620.7 | - | 0.0 | - | 0.0 | 359.4 |
| Sicily | 402.1 | 3994 | 816.8 | - | 0.0 | - | 0.0 | 0.0 |
| Sardinia | 149.9 | 4129 | 853.3 | - | 0.0 | - | 0.0 | 0.0 |
| Italy | 5040.4 | - | 6243.7 | - | 235.0 | - | 804.0 | 0.0 |

[a] *Positive if inlet*

## 4 Conclusions

This study involved the definition and development of dedicated simulation models able to represent the energy system behaviour in long-term scenarios featuring a strong sector integration and a very high presence of renewable generation, implementing a multi-node spatial detail and a multi-vector system operation.

The simulations of the Italian prospective energy system considered an hourly time resolution, whereas the spatial resolution followed the electric market areas. Within each node, the electricity balance assumes a dispatch priority for the direct use of RES, then exploits inter-zonal exchange and storage systems, eventually relying on P2H and P2P to minimise both the residual load and the curtailment of surplus generation. The transport sector enters the electricity balance by means of the demand by plug-in vehicles as well as by the need for hydrogen production via P2H for FCEVs. These two vehicle categories are the main zero-emission options that will surge in clean integrated scenarios.

The 100% RES pushed for the massive increase in solar PV capacity, given that this is the most abundant resource in Italy and assuming a large techno-economic potential for wind energy. The required installed capacities of electric RES and energy storage systems appear to be extremely high (e.g., more than 20 times today's installations in the case of solar PV), but in general positively influenced by sector integration strategies and energy vector multiplicity. Results show the massive need of over 500 $GW_p$ of PV capacity when the installation of wind capacity is limited to the estimated techno-economic potential of 60 $GW_{nom}$. If the PV installed capacities are limited to the techno-economic potential of 230 $GW_p$ currently estimated for rooftop plants on buildings and residual or abandoned rural/industrial areas, the need to satisfy the expected consumption yields a surge in import requirements, to be originated from renewables elsewhere.

The 100% RES scenario showed that energy storage systems are essential for system operation and that sector integration together with energy vector flexibility are beneficial to the overall system balances.

Further development of the work will involve the definition of long-term cost and price scenarios for the identification of optimal energy system configurations based on the total annual costs, as well as the detailing of sector-specific decarbonization efforts in areas such as steel and cement industries, residential and tertiary heating&cooling, fuels for maritime and aviation.

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