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The role of hydropower in decarbonisation scenarios

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ABSTRACT

An increased penetration of renewable energy sources is essential for the energy transition. A major role will be played by wind and solar, as they are widely available. Hydropower is another crucial resource, currently covering large shares of power generation (e.g., Norway, Italy, Brazil). Despite little expected growth, in a context of increasing electrification, improved integration of hydropower can play a critical role thanks to programmable operation. This work addresses the modelling of hydropower flexibility in energy system models and analyses the impact of hydropower operation on CO_2 emission-constrained scenarios. To implement the study, a detailed dataset of the Italian programmable hydroelectric plants is created, using open-source information, covering location, rated power, and storage capacity. Inflow timeseries are derived from historical operational data. These new sets of data are employed in OMNI-ES (a multi-node, multi-sector, and multi-vector energy system model) to study optimal configurations and operation of the Italian energy system in decarbonisation scenarios, such as net-zero-CO_2 and Fit-for-55 targets. Considering different operational strategies and multiple historical reference years (impacting the inflow), results demonstrate significant changes in hydropower behaviour and highlight its relevance as zero-carbon resource in terms of both power and energy output, influencing the installation of other technologies.

1. Introduction

In recent years, industrialised countries have dedicated an increasing effort in planning the achievement of carbon neutrality. This ambitious objective requires significant changes in systems and society. The energy sector is already undergoing a transformation to increase efficiency, foster the adoption of renewable energy sources (RES), and introduce clean energy vectors that do not release greenhouse gases (GHG). The installation of RES-based generation plants in the power sector is leading the transition, aiding the phase out of fossil fuel-based technologies. This trend is encouraged by institutions and supported by the scientific community.

In the European Union (EU), important initiatives, such as FitFor55 [1] and REPowerEU [2], provide targets, guidelines, and funds to accelerate investments. For countries that heavily rely on imported energy, such initiatives offer a crucial opportunity to mitigate the impact of global energy market fluctuations. This, in turn, will enhance economic stability and energy security within the EU. Increasing the presence of RES, especially those that do not depend on critical materials for manufacturing, attains low carbon emissions, while favouring a higher share of local resources.

1.1. Background

Among renewable energy options, hydroelectric power generation is a valuable asset for the energy system, leveraged in particular by programmability, unlike solar and wind plants. Focus is here given to dam-based systems. Hydropower flexibility is enhanced by its ability to store energy, so that an optimised use of water basins would be a valuable solution to mitigate the impact of fluctuating RES while moderating the need for new and costly energy storage technologies such as batteries. Furthermore, the construction of hydropower plants does not require critical materials, such as those required for photovoltaic (PV) panels and batteries, which are becoming crucial resources for countries with limited availability. However, hydropower also has some disadvantages compared to other RES-based plants. First, the installation of new capacity is limited by environmental constraints and restricted resources. In European countries, the most suitable sites have already been exploited and a wide expansion is not envisioned. In addition, hydroelectric power generation is strongly correlated with

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climate conditions and is therefore impacted by climate change, as resource availability and plant operation depend on weather and precipitations [3]. This dependency becomes particularly evident during dry years, when hydropower's contribution to the electricity balance reduces. These factors make hydroelectric power a compelling topic for research in the field of energy system transition for reducing CO_2 emissions.

Energy System Models (ESMs) are the common tool to investigate future scenarios at regional or country scale [4]. They may account for the electric sector alone or broadly integrate multiple energy sectors (heating and cooling, industrial, fuels for mobility, …). In essence, the computational structure of ESMs relies on solving the hourly balances of energy vectors (e.g., electricity, gas, hydrogen, liquid fuels), taking into account the availability profiles of the various energy sources, the operational constraints of the conversion technologies, and the demand profiles for each final sector (often assigned exogenously) [5]. Snapshot assessments consider a single future year, typically with a perfect foresight approach (i.e., full knowledge of past and present system behaviour at each time step). Long-term models, instead, look at a multi-year horizon, aiming to understand the progressive changes [6]. Despite the uncertainty of input data, results from ESMs enable an understanding of trends and cross-impacts between technologies and comparative scenarios, offering a rich basis for discussion.

In ESMs, the hydroelectric plants are typically modelled considering power and energy constraints, based on rated power and available resource, neglecting environmental and hydrological aspects [7]. This simplified approach, which differs from water sector models that include the detailed hydrological constraints, is justified by the complexity of ESMs and their goal to satisfy energy demands, prioritizing electricity generation over other water reservoir uses. External constraints, such as guaranteed water flow for other purposes like irrigation or navigation, can be accounted for by properly modifying the resource availability data. The spatial resolution of ESMs typically aggregates plants, making the implementation of more detailed environmental and hydrological descriptions, which are specific to individual plants, impractical. Integrating hydropower effectively into ESMs as a flexible resource poses significant challenges, which has not been widely tackled by existing studies. This is due to the constrained availability and operational boundaries, which depend on the water inflow, the reservoir size (energy capacity), and the rated output (power capacity). The first relates to precipitations and weather, whereas the second and third are technical features of the plants.

The main need for hydropower representation in ESMs is a set of detailed information, currently not available or inconsistent, with data scattered in several datasets that appear incomplete, e.g., not able to track both rated power and storage capacity for each plant. The hydropower database by the Joint Research Centre (JRC) [8], which provides data on hydropower generation with single-plant level of detail for all Europe and has been continuously updated over the years, is typically used for modelling hydropower in ESM studies [9–12]. However, data on the energy capacity of reservoirs are often not available and several plants are not included, resulting in a non-negligible underestimation of available capacity. This lack of information also affects data for Italy and is accentuated by the difficulty of obtaining rainfall inflow profiles for each hydroelectric plant. The time series are also significantly influenced by climatic variations, which depend on the reference year and affect not only hydroelectricity but must be consistent with wind and solar energy profiles [13–15].

1.2. Scope and structure of this work

The scope of this work is to study the role of hydroelectric power generation and of its flexible operation in future decarbonisation scenarios. The analysis considers the case of Italy, where a significant hydroelectric capacity exists. The assessment is developed for two scenarios: full decarbonisation (as envisioned by the EU directive for 2050) and intermediate GHG emission reduction (such as the FitFor55 goal by 2030). The investigation adopts the OMNI-ES framework (Optimisation Model for Network-Integrated Energy Systems) [16], which optimises the total annual cost of the system, under constrained CO_2 emissions, as detailed in Section 2.

As discussed above, the analysis requires detailed information on the features of programmable hydropower plants (pumped-hydro and reservoirs) and their availability. Since existing datasets do not offer the adequate completeness, a secondary goal of this work is the development of a new database, exploiting open-access data and providing the resulting information to the scientific community. The database provides the storage capacity, geographical location, and nominal power of each plant, as well as historical inflow time series by region (NUTS-2 areas).

The novelty of the proposed approach lies in the extension of the OMNI-ES framework to accommodate flexible hydropower operation for reservoir-type plants, tracking inflow-based and storage capacity-constrained behaviour, and in the development of analysis exploiting the developed database of hydroelectric facilities. The analysis looks also at the variability of weather data due to the use of different historical years as climatic reference for the input data.

The structure of this article is as follows. The adopted framework and the additional modelling elements are presented in Section 2. Then, Section 3 describes the developed methodology for gathering and processing the required data. In Section 4, the analysed scenarios are described, together with the assumptions for simulations. The results are then shown and discussed in Section 5. Finally, the key conclusions are drawn in Section 6.

2. Modelling hydropower flexibility

This section presents the developed methods to integrate hydropower flexibility into integrated ESM. The OMNI-ES model [16] is used to investigate the Italian energy system, introducing a detailed assessment of hydropower operation. OMNI-ES is based on a multi-node formulation with regional (NUTS-2) resolution, and it solves the energy balances on an hourly basis considering a target year (e.g., 2050 or 2030 in this work), adopting a perfect-foresight approach. The model optimises the national energy system by minimising the total annual cost (including both capital and operational expenditures), covering all end-use sectors (residential and services, industry, road mobility, aviation, and navigation) and considering capacity expansion for all the included technologies.

2.1. Energy system model

As Fig. 1 shows, OMNI-ES encompasses multiple energy vectors and the related transport networks. Electricity, gas, hydrogen, and liquid fuels are the considered energy vectors. Methane accounts for both fossil natural gas and biomethane, and the blending with hydrogen in the existing gas infrastructure is enabled. In this way, the gas network always operates with a CH_4-H_2 blend, with variable fractions of methane (G-CH_4) and hydrogen (G-H_2). The evolution of the gas infrastructure is considered, according to projections by the Italian gas grid transmission system operator (TSO), which foresees the possibility to exploit the existing grid to deliver a blend of methane and hydrogen. The model encompasses different types of liquid fuels (oil-based, biofuels, and e-fuels), which are treated in terms of energy content and are assumed to have the same physical properties despite different production pathways, costs, and carbon footprint of the supply chains. The flows of CO_2 are tracked considering carbon sources (combustion of fossil fuels, emissions related to the supply chains of imported energy vectors), sinks (carbon capture and storage, direct air capture), and utilisations (conversion to e-fuels), in order to introduce constraints on the system net emissions. Model results provide the optimal configuration and operation of the multi-sector integrated energy system in terms of installed

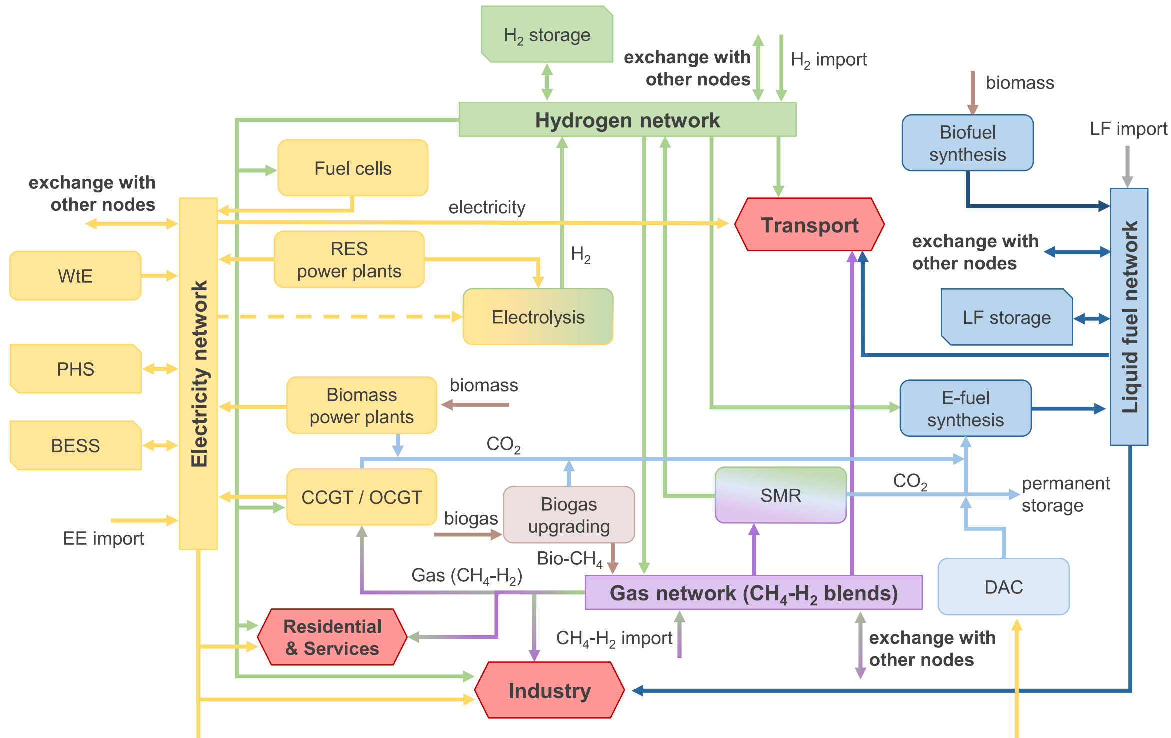

Fig. 1. Nodal balances of energy vectors and CO_2 flows as represented in the OMNI-ES framework (adapted from [16]).

capacities, domestic and imported energy resources exploitation, and flows of energy vectors and CO_2. A detailed description of the adopted modelling framework can be found in Ref. [16].

2.2. Hydroelectric power generation

Electricity generation through hydropower plants is a mature technology that widespread all around the world in the last centuries. Three main categories exist: hydro water reservoir (HWR), pumped hydro storage (PHS), and run-of-river (RoR). HWR plants exploit dams to store water in natural or artificial basins for both short- and long-term periods, enabling operation as a programmable source. PHS plants are similar, with the additional possibility to pump water back to the upstream basin, allowing for cyclic operation. Accordingly, HWR and PHS guarantee dispatchable electricity, and their operation can be optimised based on the needs of the grid and on the market prices. Their operation may also be constrained by upstream conditions (e.g., risk of overfilling the dam due to weather events) and downstream uses (e.g., irrigation). RoR plants, instead, exploit the natural flow of rivers to generate electricity, thus representing a non-programmable source.

In ESMs, two primary approaches are commonly employed to represent hydropower. One assumes historical hydropower electricity generation as an exogenous input, while the other optimises hydropower operation based on water inflow profiles as input [7]. For the purpose of this analysis, these two options are investigated. The first approach adopts an assigned operation profile of HWR plants, according to the historical generation profiles in the selected reference year. In the second approach, the operation of HWR plants is instead a decisional variable of the model. Thus, HWR plants in a generic region r and time step t must be characterized by a storage term and they must respect the energy balance between storage content, inflow, and power output, as described in Eq. (1):

$$Q_{HWR}^{r,t+1} = Q_{HWR}^{r,t} + \widetilde{q}_{inflow,HWR}^{r,t} - \frac{q_{otp,HWR}^{r,t}}{\widetilde{\eta}_{otp,HWR}} \tag{1}$$

where $Q_{HWR}^{r,t}$ is the energy storage content, $\widetilde{q}_{inflow,HWR}^{r,t}$ is the inflow (see Section 3.2), and $q_{otp,HWR}^{r,t}$ is the output power generation. Specifically, the inflow $\widetilde{q}_{inflow,HWR}^{r,t}$ is an exogenous input data, while the storage content $Q_{HWR}^{r,t}$ and the power output $q_{otp,HWR}^{r,t}$ are model variables which are endogenously optimised.

In both the historical and optimised HWR operation strategies, the behaviour of the PHS plants is endogenously optimised by the model according to Eq. (2), which represents the energy balance, differing from Eq. (1) just for the presence of two inlet contributions (inflow and pumping):

$$Q_{PHS}^{r,t+1} = Q_{PHS}^{r,t} + \widetilde{q}_{inflow,PHS}^{r,t} + q_{ipt,PHS}^{r,t} \cdot \widetilde{\eta}_{ipt,PHS} - \frac{q_{otp,PHS}^{r,t}}{\widetilde{\eta}_{otp,PHS}} \tag{2}$$

where $Q_{HWR}^{r,t}$ is the energy storage content, $\widetilde{q}_{inflow,PHS}^{n,t}$ is the inflow (see Section 3.2), $q_{ipt,PHS}^{r,t}$ is the pumping power, and $q_{otp,PHS}^{r,t}$ is the power output.

The proposed new database (see Section 3.1) provides the hourly profiles of natural inflow and the available storage capacity of HWR and PHS plants, which constrain the storage content in each region. To provide a realistic assessment, the initial level of the basins is imposed equal to the historical one at the first hour of the year. The level at the end of the year is instead imposed to be greater than or equal to the minimum value between the initial storage content and the historical end-of-year level. As detailed in Section 4.1, different weather years are compared in order to investigate the impact and behaviour of hydropower in years with different rainfall levels.

3. Dataset of Italian hydropower plants

This section introduces the procedure to derive the data required for modelling hydroelectric programmable plants. This encompasses the development of a detailed database of Italian hydropower plant (Section 3.1) and the methodology to compute the water inflow profiles for each region (Section 3.2).

3.1. Italian programmable hydropower plants database

Analysing the relevance of HWR and PHS in the future Italian energy system requires detailed data for each plant. Italy has a great history in hydropower, started in 1895 with the construction of the first plant near Milan and followed by large investments during the 20th century. The morphology allowed to invest not only in RoR but also in HWR and PHS plants providing a diversified portfolio of hydroelectric technologies. Most regions have a non-negligible installed capacity, thus representing a resource distributed all over the country, with the highest share in the Alpine regions. This brought hydroelectric to represent a relevant source of energy having a steady share around 20 % of overall Italian electricity generation [17]. In recent years, the depletion of optimal sites for the construction of new facilities has led to a decrease in new installations, maintaining the overall capacity almost constant. Just small hydropower plants have seen an increase due to their limited environmental impact and costs [18]. However, their size is small in power capacity and almost negligible in storage content and for these reasons they are not impacting significantly on the overall system. Compared to other renewable technologies such as solar photovoltaic and onshore wind, which are expected to increase dramatically in the next years [19], hydropower's limited potential for future expansion may lead to a decreased relevance in the Italian energy system. Indeed, according to the long-term strategy proposed by the Italian Ministry for Environment, non-programmable photovoltaic solar is projected to increase the installed capacity by an order of magnitude while hydroelectric is expected to keep a capacity similar to the current one. Although hydroelectric power generation faces limited opportunities for expansion, it could still provide a crucial contribution to the energy system. Especially looking at its programmable technologies (HWR and PHS) which offers the possibility to store energy for long periods (from weekly and monthly to seasonal), reducing the curtailment of non-programmable RES and at the same time limiting the installation of additional storage technologies, such as battery energy storage systems (BESS).

This brief introduction points out the importance of hydroelectric power in the Italian energy system and highlights the need to analyse it in detail when future scenarios are investigated. This must be realized through an exhaustive set of data regarding the installations, comprising both rated power and storage capacity, together with geographical coordinates to properly locate each plant. The importance of high spatial resolution emerged in recent studies which pointed out that grid dispatchability may not be guaranteed in energy system where non-programmable RES dominate, highlighting the need of having a higher spatial resolution to incorporate possible congestion limits [10, 16].

The main available databases to provide such pieces of information are those from ENTSO-E [20], Terna (the electricity TSO in Italy) [17], and JRC [8]. However, each of them lacks some of the desired details. Looking at the spatial resolution, the first two sources return reliable data pertaining to national or bidding zone characteristics, albeit they do not contain further detail (e.g., regional or provincial). On the other hand, the JRC database provides data with single-plant spatial resolution but it does not contain all the hydropower plants. In terms of overall power capacity, the three sources vary by up to 20 %. Differences are partly due to the use of diverse thresholds as minimum rated power for inclusion in the database. Terna and ENTSO-E make a distinction between HWR and RoR according to the 'reservoir duration', whereas JRC does not clarify. In the datasets by Terna and ENTSO-E, the combined capacity of these two technologies is similar, but the adopted classifications result in different shares of capacity by technology. According to the ENTSO-E database, HWR is defined as a plant with a reservoir duration of more than 24 h [20]. In contrast, Terna defines it for values over 2 h. In order to be consistent with the generation profiles provided by Terna, this work is in accordance with its classification. Storage capacity represents the least covered domain. ENTSO-E and Terna provides the filling profiles with bidding-zone resolution, which are not sufficient to conduct analyses at higher spatial details. The JRC dataset identifies the storage capacity as an attribute, but values are not present for most plants.

To fill these gaps, this work develops a comprehensive dataset of Italian HWR and PHS plants, detailing the rated power and the storage capacity, together with the location of each plant.

The JRC database includes around 400 plants with indication of punctual location and rated power (for PHS, distinguishing pump and turbine operation), for a total of 19.4 GW_e. Among these, 130 plants are HWR or PHS, and they constitute the basis for the new dataset. However, the official number of hydropower plants according to the Italian TSO is approximately 4000, with a total capacity of 24.7 GW_e [21].

Aiming to compensate for these differences, a comparison with other databases and sources is performed. So, detailed research is conducted to fill in the required information, using freely accessible data. The sources used for this research include the plant owner's websites, the Italian Ministry of Infrastructure, newspaper and magazine articles, and geographical software for data derivation. However, it is often challenging to find the storage capacity as it is rarely directly reported.

For this reason, for each plant the energy storage capacity C is derived from the water capacity of the respective basins (C_{water}, expressed in m^3), which is converted according to the definition of gravitational energy, through a plant-specific average head H (in metres) and an average turbine efficiency (η). This conversion is expressed by Eq. (3):

$$C = C_{water} \cdot \rho \cdot g \cdot H \cdot \eta \tag{3}$$

where ρ is the water density (1000 kg m^{-3}) and g is the gravitational acceleration (9.81 m s^{-2}). The head H indicates the average distance from the dam to the turbine where the conversion into electricity occurs. In the cases for which the plant head is not explicitly provided, it is estimated from topological data. The turbine efficiency is assumed equal to 87 % considering a reference value for a plant featuring a Pelton turbine. This assumption is conservative in many cases, since several plants adopt turbines with higher efficiencies, such as Francis ones. Both C_{water} and H are not fully provided by the JRC database and are as well researched. Regarding water capacity, the main source is the Italian Ministry of Infrastructure, while information regarding the plant average head is found in plant owner's website or derived using topological data.

The resulting database is accessible at https://zenodo.org/records/10666905, thus providing an open-source tool to analyse in detail Italian hydropower plants. The structure allows different plants to be located using either coordinates or region codes. For the analysis presented in this work plants are aggregated at regional level to comply with the desired resolution of the ESM (see Section 2) and final values are shown in Fig. 2.

3.1.1. Comparison with existing databases

A comparison between the proposed new database and the available ones is presented in Table 1. The reported data are aggregated to compare the accuracy of each source at the same spatial resolution level. As explained in section 3.1, the difference in installed capacities between Terna and ENTSO-E mainly lies in the diverse classification of HWR and RoR plants, while JRC and the proposed new database have values included in their range. Regarding PHS capacity, the sources are in accordance, with limited variations. It is important to notice that Terna data do not provide any information about the single plants, but only aggregations that vary from national to bidding zone levels. ENTSO-E, instead, supplies data both aggregated at national level and on single plants grouped by bidding zones. The two values do not coincide since single plants under a certain power are not listed. Regarding storage capacity, it is evident that none of the alternatives to the database created in this work provide adequate information for accurate modelling. ENTSO-E only provides the maximum values of

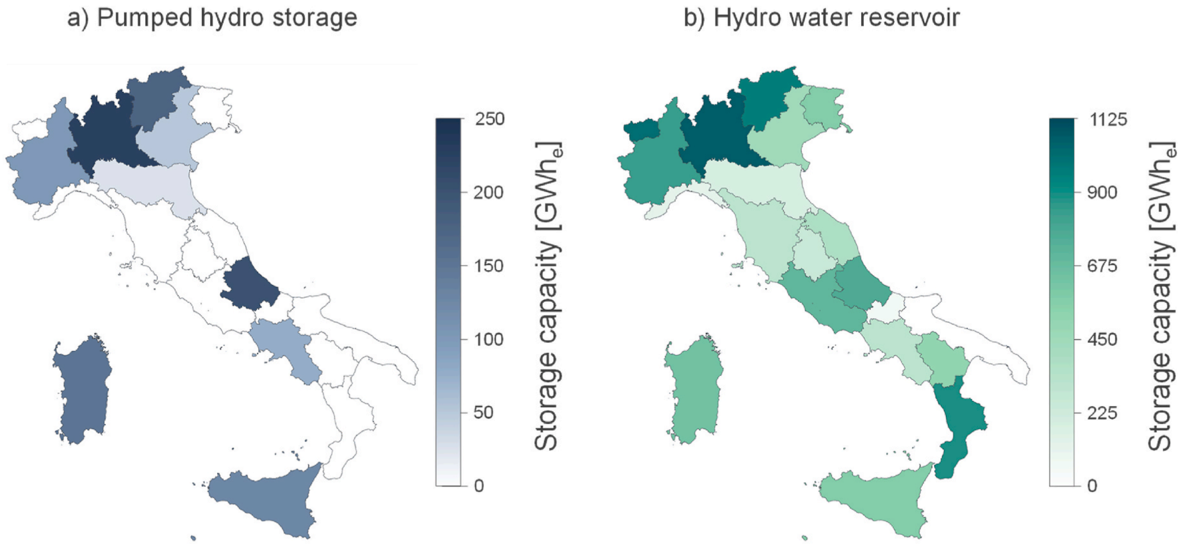

Fig. 2. Energy storage capacity by region for (a) pumped hydro storage and (b) hydro water reservoir plants.

Table 1
Comparison between Italian hydropower plant databases.

Database		Terna	ENTSO-E	JRC	This work
Spatial resolution		Bidding zones/ National	Bidding zones/ National	Geographical coordinates	Geographical coordinates
Cumulative rated capacity HWR [MW]	**Aggregated value**	10626	4542	5528	7015.93
	Sum of single-plant values	No data	3991	5528	7015.93
Cumulative rated capacity PHS [MW]	**Aggregated value**	7809	Discharge: 7256	Discharge: 7962 Charge: 6675	Discharge: 7924.0 Charge: 6809.3
	Sum of single-plant values	No data	Discharge: 6960	Discharge: 7962 Charge: 6675	Discharge: 7924.0 Charge: 6809.3
Cumulative storage capacity [GWh]	**Aggregated value**	6515	4805.22[a]	401.20	6405.26
	Sum of single-plant values	No data	No data	401.20	6405.26
Number of elements		No data	96	102	197

[a] Maximum historical content per bidding zone.

energy stored in the basins of each bidding zone, without differentiation by region or technology. This approach leads to a certain margin of error, as PHS and HWR are counted together. Terna database has a similar issue, as it only provides data for three macro-areas. However, the available data are reliable and considered the benchmark for comparison with the other two databases [22]. The proposed new database appears in line with those from Terna, having a discrepancy limited to 2 %, while the JRC database is clearly not comparable since few plants have this level of detail. The accuracy of JRC data would be not optimal also considering the contribution from all the 102 plants contained in it since, using the methodology introduced in section 3.1, the overall storage capacity would reach 4343 GW h. This gap is due not only to the plants added in the analysis but also to the aggregated contribute of concatenated plants, as stated in the Terna guidelines. In doing so, it is important to understand the units that are in series to count properly their available volume. The proposed new database, among the 197 elements, includes the contributions that allow to have overall storage content aligned with Terna's data. To conclude, this work presents an open access database, providing information for the main HWR and PHS Italian plants. These values appear in accordance with the national data provided by Terna and add the spatial resolution required to model the national energy system with a higher detail. Some small contributions are still missing, due to small plants, which however do not impact significantly the national values.

3.2. *Inflow computation*

The following step in the analysis consists of the computation of water inflow. After having defined the storage capacity it is necessary to define the natural water profile which provides the available resources to hydropower plants. To do so it is necessary to link a specific plant to the precipitation occurred in the watershed connected but the lack of data makes it difficult to be computed at plant level. Accordingly, the analysis considers the aggregate inflow by region.

Data from ENTSO-E [20] provide the starting point to derive the precipitation inflow. The source offers the time series of the aggregate filling rate of HWR and PHS basins estimating the stored energy value (SEV) aggregated by bidding zone. Thus, given the hydroelectric power generation throughout a specific period (e.g., a week), the occurred inflow can be computed defining Eq. (4), which is a balance that links the variation in the SEV to the inputs (in this work, the energy associated with the water inflow and the pumped water in the case of PHS) and the outputs (the generated energy from the turbines).

$$Inflow_i = SEV_{i+1} - SEV_i + \sum_{j=1}^{168} \left(E_{HWR,j} + E_{PHS_{gen},j} - E_{PHS_{con},j} \right) \tag{4}$$

$E_{PHS_{con},j}$, $E_{PHS_{gen},j}$, and $E_{HWR,j}$ are the electricity consumption of PHS plants for upward pumping, the electricity generated by PHS plants, and the electricity generated by HWR plants, respectively. ENTSO-E provides hourly profiles [23] for these quantities. These are then aggregated on a weekly basis throughout the year to ensure consistency with the SEV data. Hence, the subscript j stands for the hour within the week, while the subscript i denotes the week of the year. A modification of the ENTSO-E profiles is necessary to ensure consistency with the TSO data, since HWR plants have a higher capacity in the TSO data. Therefore, the total energy produced by HWR plants needs to be compensated to avoid an underestimation of the inflow. This is done by scaling the ENTSO-E profiles to the total generation per bidding zone provided by the TSO. The discrepancy between the two data providers is due to the different criteria used for the categorisation of hydropower plants. As reported in section 3.1.1, the classification is based on the time required to fill the reservoir with water.

The derived profiles reflect what is assumed to be filling or emptying the basins of the bidding zones due to natural contributions only (i.e., precipitation, evaporation, icing). In Fig. 3, the year-long inflow profile is presented for two representative bidding zones (Centre-North and Sardinia). Seasonal patterns are evident, differing in the two areas. In the case of Sardinia, very low summer precipitations occur, and seasonal storage is required to enable hydropower production during summer months. Negative inflow values are also featured. This may derive from ice formation (the trend noticeable in Alpine regions characterized by negative values in first weeks of the year) and water evaporation in hot periods. In other instances, this may be due to maintenance of dams, which can require to empty the whole basin. Other reasons include the minimum vital flow of rivers downstream the basin, which is imposed by legislation also when the hydropower plant is not running, resulting in spilling from the reservoirs. An example of this happens in southern regions in summer when no precipitations occur, and hydropower plant are tuned off. Furthermore, Fig. 3 depicts how precipitation can be highly concentrated in time, highlighting the importance of water storage to regulate river flows.

Fig. 4 depicts the inflow duration curve in the bidding zone Sardinia for four different years. The profiles show that precipitations can vary significantly. It is clear how 2022 profiles have a lower duration curve due to the drought occurred in that year and this anticipates how the choice of different representative years has an impact in the optimised energy system model.

The derived inflow profiles need to be distributed between the two different technologies (i.e., HWR and PHS) and across the regions that compose each bidding zone. This is achieved by splitting the inflow in proportion to the regional energy capacity of the HWR and PHS plants (as derived above). This is equivalent to assuming that plants with larger capacities benefit from a proportionally larger share of the bidding zone inflow.

4. Scenario definition

The analysis performed in this work looks at the case of Italy. This section details the investigated scenarios, encompassing the selection of the historical climatic years used as reference (Section 4.1) and the imposed targets and sectors' characteristics for the full (section 4.2) and intermediate (section 4.3) decarbonisation.

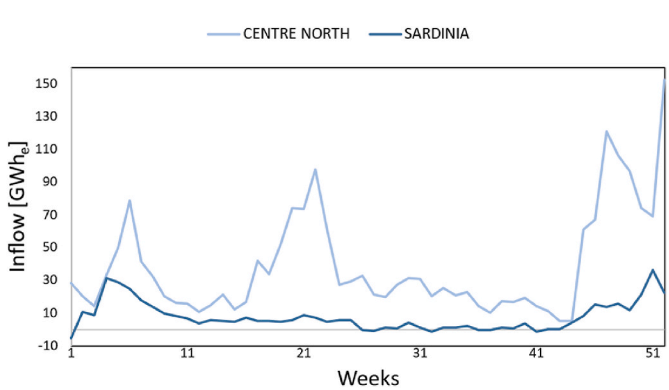

Fig. 3. Year-long hourly profiles of inflow in the Centre-North and Sardinia bidding zones.

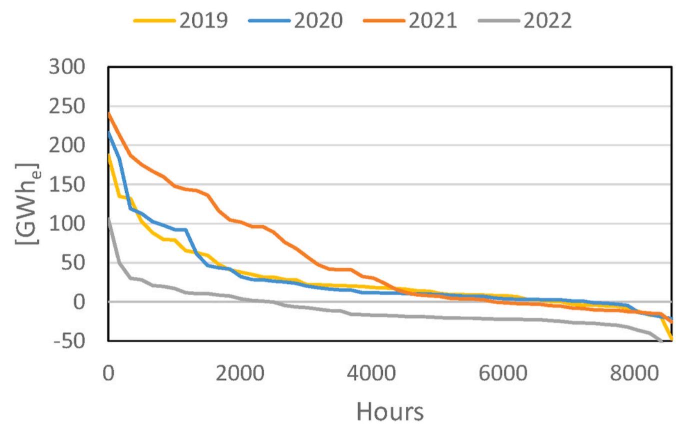

Fig. 4. Inflow duration curve in bidding zone Sardinia, in four different years.

4.1. Reference years

An impactful aspect is the variability caused by the weather conditions, which can vary significantly from year to year, resulting in different sets of input data for the model. This study considers four different reference years, extracted from historical data (2019–2022), to understand the role of hydroelectric power in various conditions. All these conditions affect renewable energy profiles, such as wind, photovoltaic, and water inflow, as well as final energy vector demand (e.g., for heating and cooling, which are influenced by mean ambient temperature). Table 2 highlights the variations of the main quantities in the considered historical years. For instance, it is evident that hydropower generation was significantly impacted by the extreme drought conditions experienced in 2022.

4.2. Full decarbonisation scenario

The OMNI-ES model is applied to investigate the role of hydroelectric power generation in a long-term scenario for Italy, looking at the achievement of economy-wide carbon neutrality in the target year 2050. The assumptions underlying the analysed scenario are outlined in the remainder of this section, while a more detailed discussion may be found in Ref. [16].

The demand quantity and hourly profiles of each energy vector is determined considering the evolution of all end-use sectors towards the adoption of decarbonized options and assigned exogenously to the model. Fig. 5 summarizes the energy vector demand, showing the energy vector share on the final demand of product/services and the total annual consumption of each sector.

The electricity demand encompasses the evolution of the conventional consumers load based on population and gross domestic product

Table 2
Main input quantities in the historical years considered. Photovoltaic and wind equivalent hours are a mean across all the regions profiles, while RoR production and inflow are the sum of all the regions.

Quantity	2019	2020	2021	2022
PV equivalent hours	1118	1136	1086	1105
Onshore wind equivalent hours	1743	1418	1489	1414
RoR power generation [GWh]	21.14	19.93	18.49	13.53
Cumulative HWR + PHS inflow [GWh]	23.85	27.20	27.25	14.49

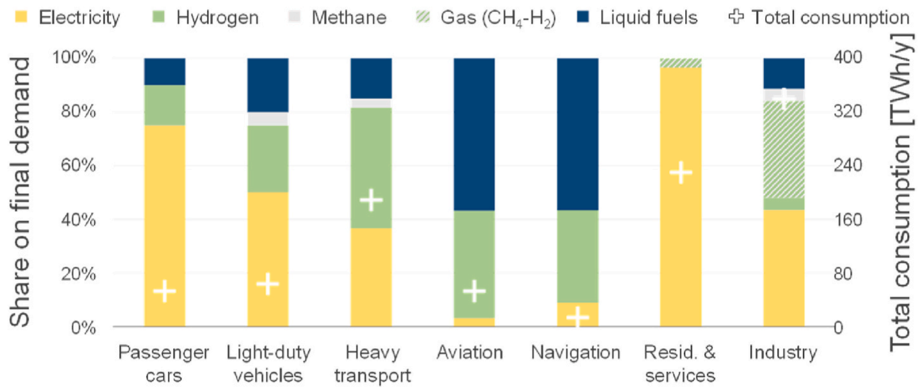

Fig. 5. Shares of energy vectors on the final demand of products/services (left axis) and total energy vector consumptions (right axis) in the full decarbonisation scenario. Heavy transport includes heavy-duty vehicles and buses.

(GDP) growth and increased electrification in households, as estimated by the transmission system operators [24], and the additional contribution of electrified space heating, transport, and industrial heat generation. The direct gas demand consists of a residual use of gas systems for space heating and cooking, and high-temperature industrial heat generation, and it can be satisfied with a blend of methane and hydrogen with unlimited hydrogen fraction. Pure hydrogen encompasses used in applications in the transport sector and in industry, while the demand of liquid fuels consists of uses in aviation, navigation, industry (as chemical feedstocks), as well as a residual use for internal combustion engine vehicles. In all the cases, carbon-neutral fuels of either synthetic or biogenic origin can be exploited to cover the demand.

Space heating is mostly electrified, with 75 % of the thermal demand covered via electric heat pumps, 15 % via district heating, 5 % via gas absorption heat pumps, and 5 % via biomass boilers. The electricity demand for space cooling is defined to account for thermal comfort needs. The hourly-resolved profiles for each technology are determined following the methodology presented in Refs. [25–27].

Demand shares in transport are determined based on recent long-term projections [28,29]. As summarized in Table 3, the analysis considers a significant presence of battery electric vehicles (BEVs) in light mobility, while heavy transport relies also on hydrogen-and liquid fuels. The current reliance of part of road transport on pure CH_4 is maintained, with use of either natural gas or biomethane. The possibility of smart charging is enabled for passenger car BEVs. Demand shares for aviation and navigation are assigned considering the national consumption as reported in Fig. 5, taking into account both passenger and freight transport.

The industrial demand of energy vectors is built from historical consumptions [30], considering the adoption of decarbonized technologies. Complete electrification of low-temperature (<100 °C) process heat generation is assumed (excluding the systems already based on biomass, geothermal, and solar energy), while medium- and high--temperature (>100 °C) heat generation is assumed to be converted to gas boilers, which can be fed by a CH_4-H_2 blend with hydrogen fraction

Table 3
Road transport stock share assumptions.

Category	ICEV-LF	ICEV-CH_4	BEV	FCEV
Passenger cars	10 %	–	75 %	15 %
Light-duty vehicles	20 %	5 %	50 %	25 %
Heavy-duty vehicles	20 %	10 %	10 %	60 %
Buses	15 %	–	50 %	35 %

up to 100 %. In the chemical industry, all fossil-based feedstocks are assumed to be converted to carbon-neutral options. Accordingly, hydrogen replaces natural gas in ammonia and methanol production, while carbon-neutral methanol substitutes naphtha in high-value chemicals (HVCs) and BTX (benzene, toluene, and xylenes) [31]. Blast furnace-based primary steelmaking is assumed to switch to Direct Reduction of Iron ore (DRI) and Electric Arc Furnaces (EAFs), with half of the production relying on methane and half on hydrogen as DRI feed. The implementation of carbon capture and sequestration (CCS) is imposed for the methane-based production. GHG emissions from cement manufacturing are also assumed to be abated via CCS.

The potential for renewable energy sources is taken from Ref. [16]. Considering rooftop- and ground-based installations, the solar photovoltaic potential is estimated in 405 GW_e, while the wind speed and the geomorphological features of the territory limit the onshore wind potential to 224 GW_e. Based on the areas with suitable wind intensity and seabed morphology for piled foundations [32], the offshore wind capacity is set to 9.5 GW_e. For thermoelectric power generation, the analysis considers the phase out of oil- and coal-based plants and the revamping of combined-cycle gas turbines (CCGTs) and open-cycle gas turbines (OCGTs) with the installation of high-efficiency devices, which can be fuelled with a blend of CH_4 and H_2 with unconstrained H_2 fraction. Since revamping generally involves the installation of larger machinery, the maximum capacity of CCGTs and OCGTs is set 50 % higher than current values (resulting in 83 GW_e for CCGTs and 5 GW_e for OCGTs). The biomass-based power generation potential is assumed equal to today's installed capacity (4 GW_e), as biomass availability is the most limiting constraints for its use. The operation of Waste-to-Energy plants is kept unvaried (1 GW_e of installed capacity) [33], while only a slight increase of geothermal (+10 %, reaching 1 GW_e) and run-of-river (+20 %, reaching 7 GW_e) capacity is considered as most available areas have already been exploited. For the same reason, the installed capacity of HWR and PHS systems is assumed unvaried (see Section 3 for the discussion on the current status of hydroelectric power generation).

For domestic sources, domestic gas production is limited to the 2019 value, equal to 47 TWh_{LHV}/y, considering both onshore and offshore wells [34]. The availability of biomass is equal to 52 TWh_{LHV}/y considering waste and residual solid biomass exclusively [35], while the biomethane production potential corresponds to 55 TWh_{LHV}/y considering the upgrading of biogas produced from livestock residues and biodegradable waste [35,36]. For permanent CO_2 sequestration, an annual storage capacity of 20 Mt_{CO2}/y is assumed as maximum amount, corresponding to the lower boundary of the range indicated in the national long-term strategy [19].

4.3. Intermediate decarbonisation scenario

The intermediate decarbonisation scenario assessment considers the achievement of the objectives set by the Fit for 55 (FF55) [1] and REPowerEU [2] packages, which look at the target year 2030. These consist of an overall (all sectors) 55 % GHG emission reduction with respect to 1990, and of a 43.7 % GHG emission reduction in non-ETS sectors with respect to 2005. EU regulations require the first objective to be achieved at the European level. Nevertheless, it is here applied at the country level to consider that all countries need to transition towards decarbonisation. The second objective interests the so-called Effort Sharing Regulation (ESR) sectors, i.e., transport, residential and services, and small industry, and is set at the country level with a dedicated target.

Fig. 6 summarizes the system demand, showing the energy vector shares and total demand by sector. The road transport sector is assumed to evolve according to the estimates of the National Energy and Climate Plan (NECP) [37], which assumes the deployment of 6 million plug-in electric vehicles (4 million BEVs + 2 million PHEVs). A minor presence (1 %) of FCEVs is assumed in heavy-duty trucks. Based on ISPRA's mobility scenarios, a modal shift towards public and shared mobility is considered, resulting in a 6 % reduction of passenger-kilometres. As indicated in the national energy and climate plan (NECP), the renewal of the fleet of public buses requires new purchases to consists of electric vehicles and externally rechargeable hybrid vehicles, as well as natural gas and hydrogen vehicles for at least 30 % by 2022, 50 % by 2025, and 85 % by 2030 [37]. In industry, a partial electrification of low-temperature process heat generation is considered, assuming that heat pumps cover 25 % of low-temperature heat currently generated with fossil fuels. The pure hydrogen demand in industry (see Fig. 6) corresponds to today's hydrogen demand of refineries. Hydrogen can also be employed in a blend with methane, with a maximum fraction (on energy bases) of 5 %, for applications that consume gas (boilers and gas turbine-based power generation units). Feedstocks for the production of chemicals are assumed unvaried with respect to today's technologies. Finally, the analysis takes into account a strong electrification of building heating based on FF55 indications, resulting in a 70 % reduction of the natural gas consumption in the sector.

On the supply side, RES power generation capacity is bounded by the values indicated in the NECP (80 GW_e for PV, 26 GW_e for onshore wind, and 2 GW_e for offshore wind) [38]. Hydrogen can be produced domestically via either electrolysis or steam methane reforming. To diversify the supply, blue hydrogen production is imposed to cover 50 % of the exogenous demand (i.e., refineries and FCEVs). Potentials of biogenic sources are updated to medium-term projections (25 TWh_{LHV}/y and 27 TWh_{LHV}/y for biomass and biomethane, respectively), together with natural absorption of CO_2, which is set equal to the NECP target for 2030 (36 Mt_{CO2}/y).

5. Results and discussion

The analysis looks at the cost-optimal energy system configuration in GHG emission-constrained scenarios, comparing the case of assigned HWR plant operation with that of optimised HWR operation. The assessment is repeated by changing the reference climatic year to depict trends and impacts in different conditions. To evaluate the variation in the role of hydropower under different GHG emission constraints, two scenarios are studied: full decarbonisation, detailed in Section 5.1, and intermediate decarbonisation, discussed in Section 5.2, based on the assumptions discussed in Section 4.

5.1. Full decarbonisation scenario

In this subsection the outcomes presented refer to the full decarbonisation scenario presented in section 4.2 applied to OMNI-ES model.

5.1.1. System configuration and operation

Table 4 compares the resulting installed capacities of the most relevant technologies and the electricity balance in the historical and optimised scenarios for the different reference climatic years. The introduction of HWR flexibility clearly increases the IRES installation, especially PV for the reference years 2019, 2020, and 2021 (with an increase of 7.3, 8.8, and 6.5 %, respectively) and wind for the reference year 2022 (+6.8 %), mainly due to the saturation of PV installation. Another significant change is the reduction in the need of BESS, which is also accompanied in the majority of cases by a reduction in hydrogen storage capacity. This is due to the possibility to exploit existing assets (i.e., hydroelectric plants) as storage systems, reducing the need for new installations that would cause an extra cost for the overall system. Indeed, the optimised use of HWR replaces BESS role in balancing short-term oscillations of renewable power generation. Its effect is reduced when considering 2022 as reference climatic year, due to the reduced water availability and the consequent less flexibility offered by the optimised HWR operation. The BESS/PV and BESS/IRES ratios reported in Table 4 remark this concept, showing lower values in the optimised hydropower operation scenarios. The decrease stands for a lower potentiality of BESS to store the renewable generation, meaning that the system requires a lower BESS capacity to manage all the IRES generation.

Hydrogen storage is needed to balance temporal and geographical mismatches. The installed capacities are in the range of thousands of TWh_{LHV}. These have a limited impact on the total annual cost and multiple near-optimal solutions exist at varying H_2 storage size, so that minor modifications on the system boundary conditions can result in

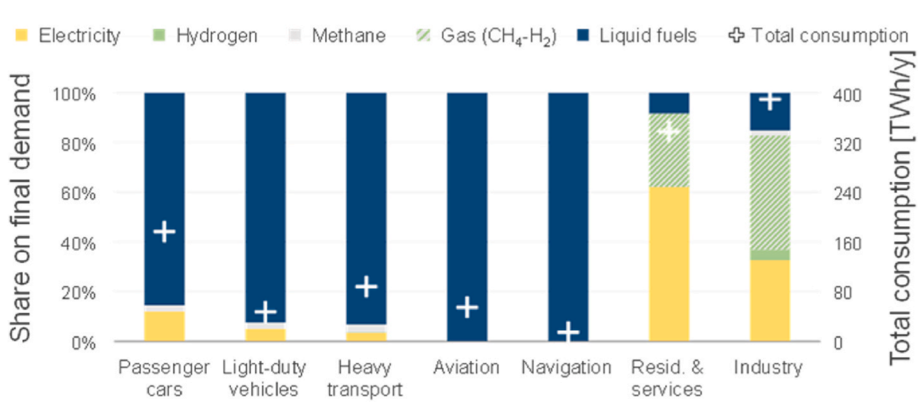

Fig. 6. Shares of energy vectors on the final demand of products/services (left axis) and total energy vector consumptions (right axis) in the intermediate decarbonisation scenario. Heavy transport includes heavy-duty vehicles and buses.

Table 4
Main features of the Italian energy system (installed capacities and annual energy quantities) in the full decarbonisation scenario (2050), for two hydropower operation options (historical or optimised) and for four different reference climatic years for the input profiles.

Reference climatic year		2019		2020		2021		2022	
Hydropower operation		Historical	Optimised	Historical	Optimised	Historical	Optimised	Historical	Optimised
Installed capacities	Photovoltaic (GW_e)	340	365	367	400	353	376	405[a]	405[a]
	Wind (GW_e)	136	135	127	126	138	143	133	142
	Thermoelectric (GW_e)	21	17	22	17	18	17	20	16
	BESS (GWh_e)	77	72	79	89	62	59	100	99
	Electrolysis (GW_e)	131	136	138	146	137	143	146	146
	H_2 storage (GWh_{LHV})	1227	1168	2859	3106	3385	3561	3327	3031
Storage utilisation	BESS/PV ratio (h)	0.23	0.20	0.22	0.22	0.18	0.16	0.25	0.24
	BESS/IRES ratio (h)	0.16	0.14	0.16	0.17	0.13	0.11	0.19	0.18
	PHS equivalent cycles (y^{-1})	27	28	27	29	29	29	28	27
Electricity generation (TWh_e/y)	Thermoelectric	19	20	21	21	21	22	22	21
	HWR	24	24	26	22	26	23	14	12
	RoR	21	21	20	20	18	18	14	14
	PV	378	403	413	444	405	402	437	437
	Wind	246	244	208	206	224	246	216	230
	Import	49	51	48	53	51	57	57	62
Curtailment (TWh_e/y)		9	10	10	11	10	10	12	12

[a] Upper boundary on installed capacity is saturated.

large variations of the computed hydrogen storage capacity, with limited changes in the overall system configurations.

The required thermoelectric capacity reduces by 6–23 % when introducing HWR flexible operation for all reference climatic years, while its generation output remains nearly constant. This proves that an optimised operation of HWR plants can contribute with dispatchable electric output to support the electric grid balance when non-programmable sources are not available, as an alternative to thermoelectric generation.

5.1.2. *Effect of operation strategies*

In this subsection, the different operation strategies of hydropower between historical and system-optimised scenarios are compared and discussed. The main effects are observed on the year-long evolution of the stored water content and on the electric energy balances. For the sake of simplicity, only one reference year is considered (2019). Trends and consideration apply similarly also in the other cases of reference years.

Fig. 7 displays a comparison of the HWR duration curve between historical and system-optimised operation strategies. The hydropower duration curve with the historical operation exhibits a smoother trend, as hydroelectricity has traditionally provided baseload generation. Enabling more flexible operation results in HWR plants exhibiting a peaking behaviour, with a shift of operating hours at high power output and a non-negligible set of hours at null or limited output. A plateau is observed when simulating the energy system with optimised hydropower operation, which can be related to periods of very high inflow that would otherwise saturate the water storage capacity. This is particularly related to a few regions with relatively small basins and may in part be due to the approximation introduced in the inflow distribution between regions (see Section 3.2).

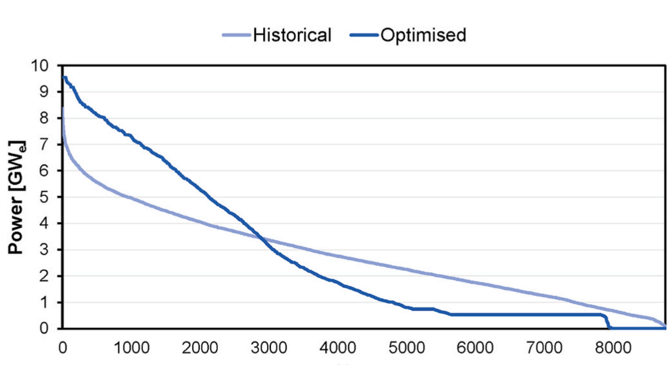

Fig. 7. Duration curves of HWR plants output in the historical and system-optimised operation strategies, at country scale, in the 2050 scenario with reference climatic year 2019.

Fig. 8 compares the year-long evolution of the storage content (cumulative HWR and PHS) in two scenarios, by bidding zone (following the zonal division of 2019 [39]). The curve of the historical case is derived from ENTSO-E data for the year 2019. The optimised scenario aggregates results of individual regions across the bidding zones, as calculated from the model run with reference climatic year 2019.

In the optimised hydropower operation cases, the model allows for variations between the maximum capacity of the basins, as determined by the analysis outlined in Section 3.1, and a minimum storage content, which is set equal to the historical minimum level of the basins. In the optimised case, all bidding zones feature more ample seasonal oscillations, resulting in a higher amount of energy being stored during summer and later discharged when other RES generation is lower. This is particularly evident for zones Centre-South and South. In certain bidding zones, such as Sicily, the difference between the two lines is limited, indicating that the space for optimisation is little, as HWR power generation is primarily driven by the availability of inflow. Also in the North bidding zone, which represents nearly 65 % of the national storage capacity, the trends in the two operation cases are similar; however, a more pronounced seasonality is evident, with differences of up to 1000 GWh_e in the energy stored during summer.

Regarding other years, the behaviour is similar for 2020 and 2021, while some changes occur for 2022 where the lower inflow gives less flexibility to the model to vary from historical operation. An example is shown in Fig. 9, where Sardinia bidding zone is analysed. It is evident how 2022 differs from the other years represented, allowing less seasonal storage.

Fig. 10 focuses on the integration between PV, wind and hydro reservoirs and compares the optimised operation scenario with historical one. The black line represents the cumulative duration curve of these three technologies, while stacked columns represent the share of HWR (in light blue), photovoltaic (yellow) and wind (green) on the generated power in each hour. Comparing the two charts, it is clear that the HWR generation changes when its operation is optimised by the model. A

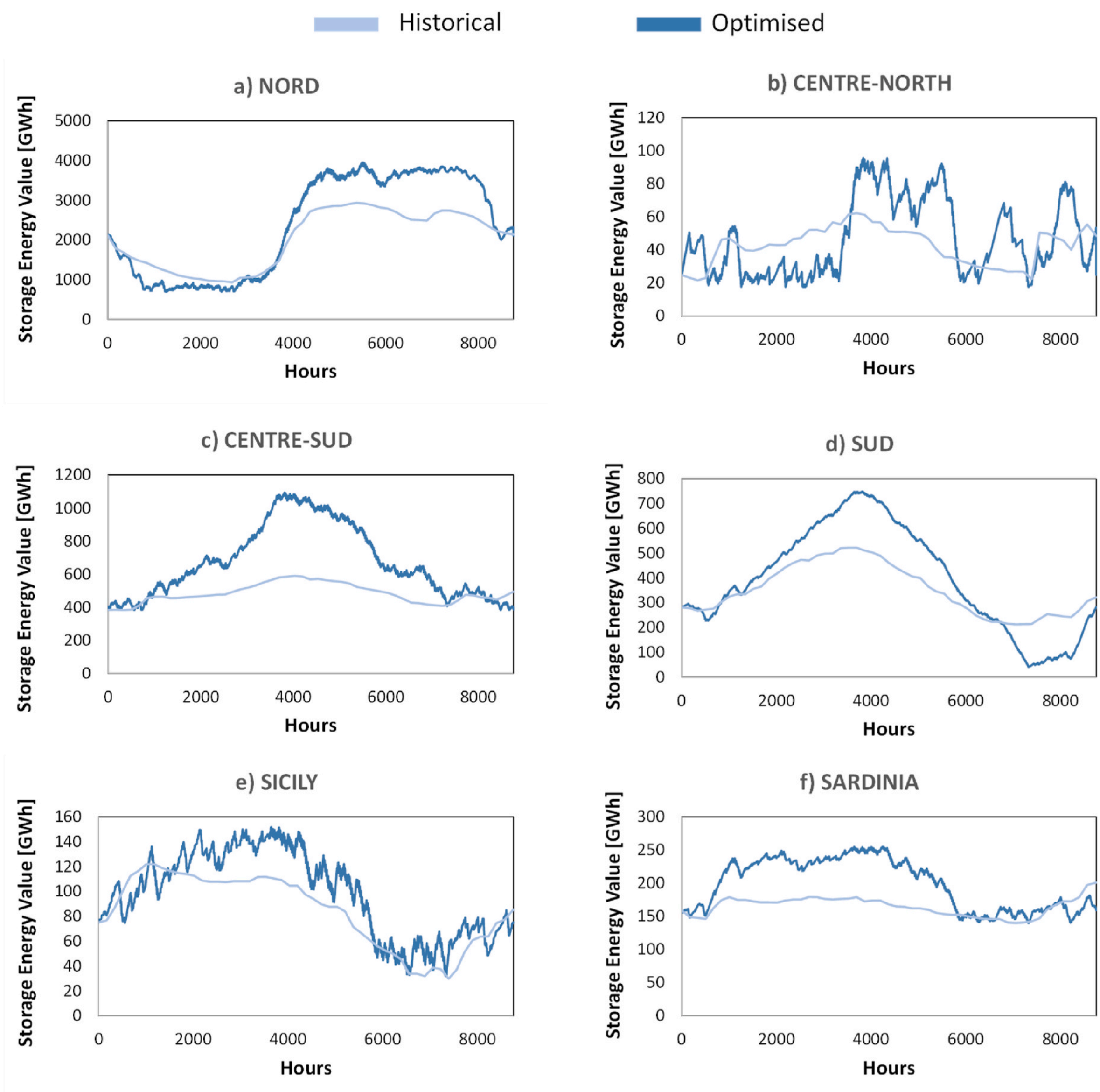

Fig. 8. Storage energy value comparison between the optimised HWR operation strategy scenario output and the historical profiles, by bidding zone, in the 2050 scenarios with reference climatic year 2019.

complementary relation between solar PV, wind and HWR is shown in the optimised HWR operation strategy scenario, Fig. 10b. Indeed, the share of hydro reservoir generation starts to appear only at low power, increasing significantly in the right part of the chart. Instead, for the historical HWR operation strategy scenario, Fig. 10a, the HWR is more distributed at higher power resulting in a lower contribution when wind and solar production is lower. This is due to the assumption of HWR operation equal to the historical generation profiles (from 2019), which were in accordance with an energy system where IRES represented a lower share compared to the full decarbonisation scenario one.

Such behaviour is also evident in Fig. 11, which highlights that hydro reservoirs are adopted to compensate lack of PV or wind generation. Regarding the coupling with solar photovoltaic, a strong daily pattern is evident, with HWR covering the load in the early morning and late afternoon and PV taking over the central hours of the day. Consistent with the trend highlighted in Fig. 7, HWR plants often operate at peak power. Instead, the comparison between HWR and wind operation features a seasonal pattern, in which HWR production is more concentrated when wind generation is low, such as summer months. PHS exhibits a comparable operational profile, generating electricity during periods when wind and PV production is limited, and driving the pumps when IRES power is at its maximum. Fig. 11 also provides insights on the effect that the optimised management of hydroelectric systems has on reducing the need for BESS capacity, with the former compensating short-term renewable generation deficits.

5.2. Intermediate decarbonisation scenario

In this section the OMNI-ES model is applied to understand the role of hydroelectric power generation in the intermediate decarbonisation scenario presented in section 4.3. Table 5 compares the installed capacities of the most relevant technologies and the electricity balance resulting from the runs with the historical and the optimised hydropower operation strategies, for the different reference years. The

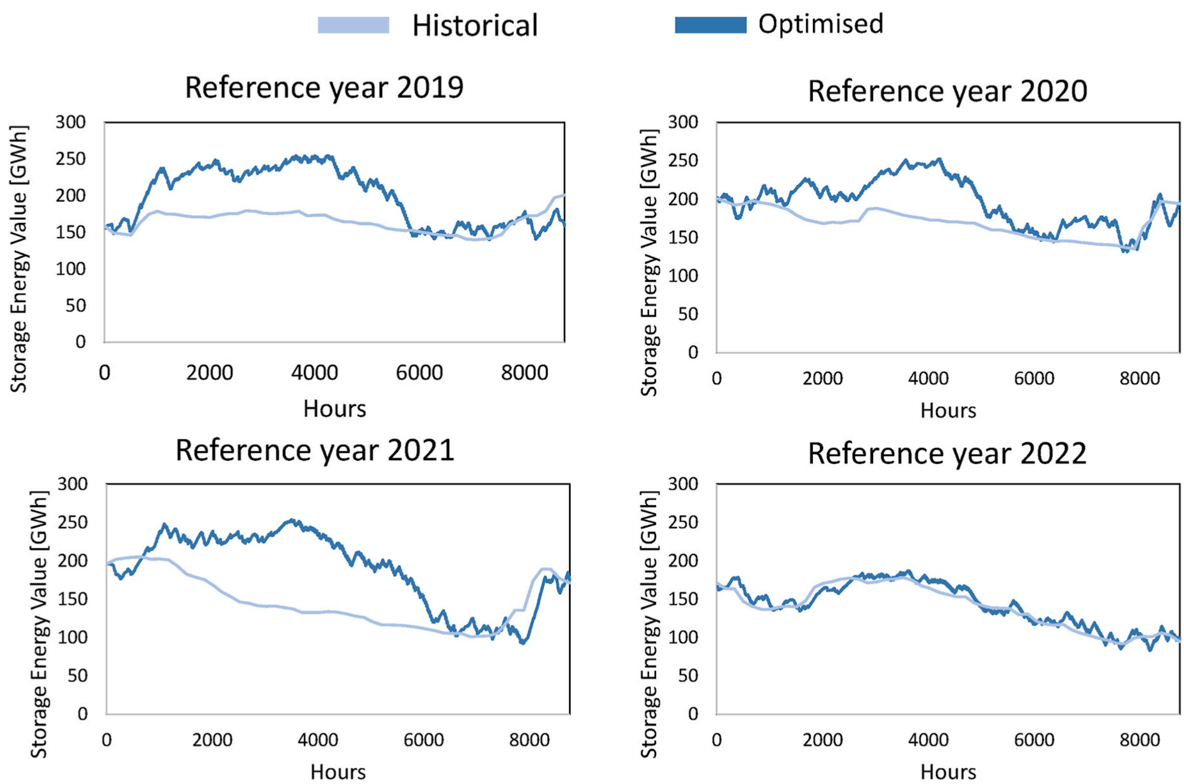

Fig. 9. Storage Energy Value in the Sardinia bidding zone in the historical (light blue) and optimised (dark blue) HWR operation strategy, in the 2050 scenario with four different reference climatic years.

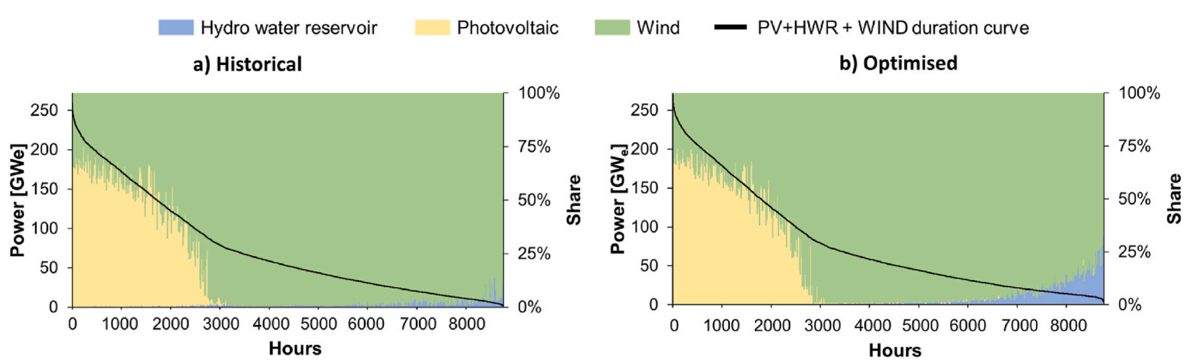

Fig. 10. Cumulative PV, WIND, and HWR duration curve (black line, left axis) and corresponding share on generated power (coloured areas, right axis), with historical (a) or optimised (b) HWR operation strategy, in the 2050 scenario with reference climatic year 2019.

outcomes are in line with those obtained in the full decarbonisation scenario, but due to the lower penetration of IRES the impact of detailed hydroelectric description is more evident. Indeed, for all the reference years both the historical and system-optimised strategy cases saturate the available potential for installation of PV and wind, and the effects of improved hydropower operation are reflected in the use of storage technologies and programmable generation. The former are characterized by a significative decrease of BESS from values around 20 GWh in the historical HWR operation strategy, with the exception of reference climatic year 2022, to no installations in the system-optimised one, while H_2 storage undergoes a reduction in the range of 3–24 %. The optimised use of hydropower allows for an improved allocation of renewable electricity, enabling greater natural gas utilisation while meeting the imposed emission targets. As a result, thermoelectric generation increases in the order of 10 % in capacity and of 15–45 % in generation. As noticed in the full decarbonisation scenario, the variations are reduced with 2022 due to the reduced water availability and the consequent less flexibility offered by the optimised HWR production.

5.3. Impact of hydropower in future scenarios

Hydroelectric power generation capacity is expected to remain nearly stable in the future, due to limited available locations for new installation, especially for large dam-based constructions. However, looking at the Italian context, the overall electricity consumption is projected to more than double by 2050, resulting in a decrease of

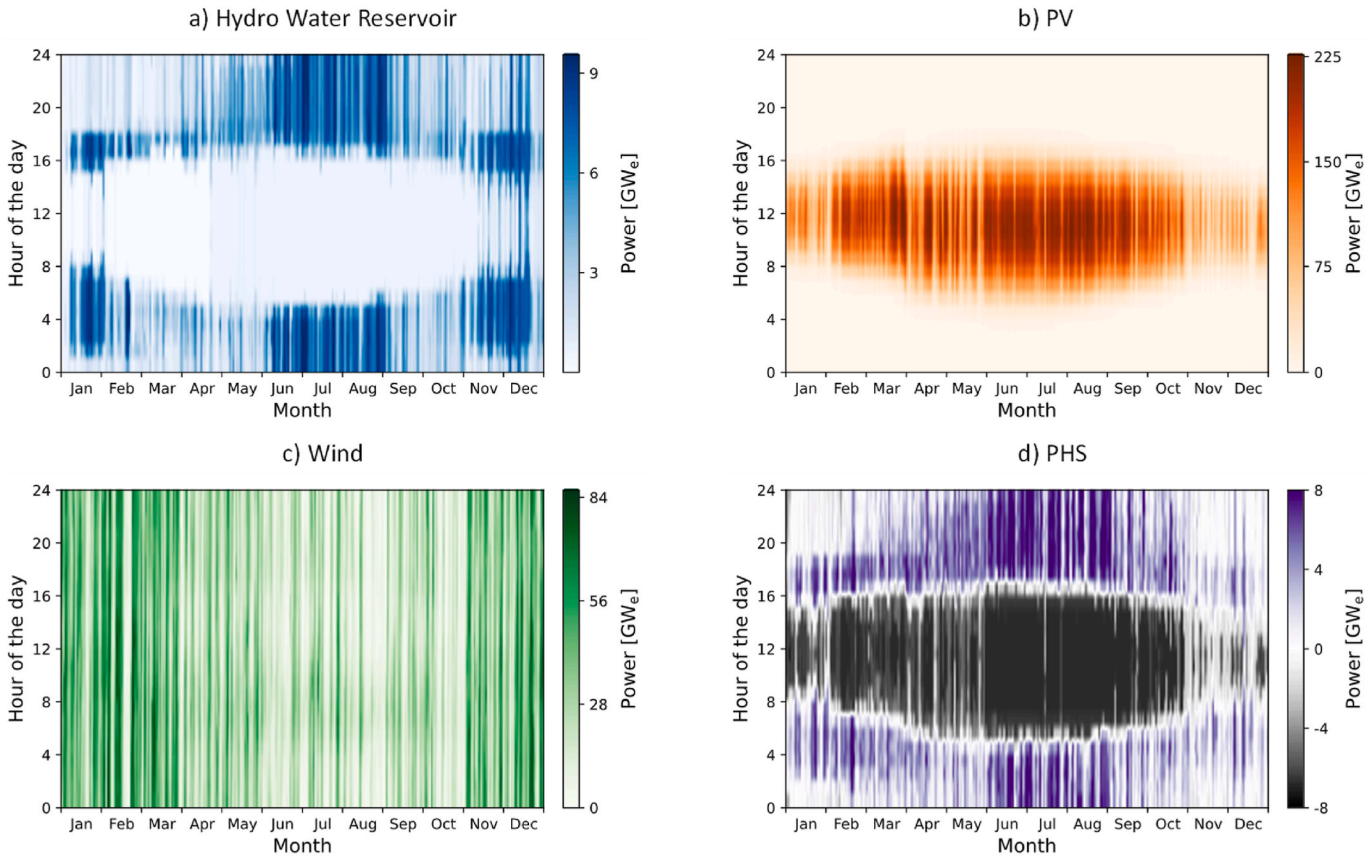

Fig. 11. Hourly power generation of hydro water reservoir (a), PV (b), wind (c) and PHS (d), with optimised HWR operation strategy, in the 2050 scenario with reference climatic year 2019.

Table 5
Main features of the Italian energy system (installed capacities and annual energy quantities) in the intermediate decarbonisation scenario (2030), for two hydropower operation options (historical or optimised) and for four different reference climatic years for the input profiles.

Reference year for climatic data		2019		2020		2021		2022	
Hydropower operation		Historical	Optimised	Historical	Optimised	Historical	Optimised	Historical	Optimised
Installed capacities	Photovoltaic (GW)	80[a]	80[a]	80[a]	80[a]	80[a]	80[a]	80[a]	80[a]
	Wind (GW)	26[a]	26[a]	26[a]	26[a]	26[a]	26[a]	26[a]	26[a]
	Thermoelectric (GW)	29	32	29	33	30	33	34	36
	BESS (GWh)	22	0	22	0	18	0	0	0
	Electrolysis (GW)	8	9	8	9	9	9	9	8
	H_2 storage (GWh_{LHV})	33	32	39	34	46	35	35	30
Storage utilisation	BESS/PV ratio (h)	0.27	0	0.27	0	0.23	0	0	0
	BESS/IRES ratio (h)	0.20	0	0.20	0	0.17	0	0	0
	PHS equivalent cycles (y^{-1})	12	9	12	9	12	9	8	6
Electricity generation (TWh_e/y)	Thermoelectric	64	86	65	93	66	94	98	113
	HWR	24	24	26	22	26	23	14	12
	RoR	21	21	20	20	18	18	14	14
	PV	92	92	93	93	90	90	92	92
	Wind	49	49	45	45	48	48	45	45
	Import	50	50	50	50	50	50	50	50
Curtailment (TWh_e/y)		2	1.6	2.8	1.8	2.8	1.9	1.9	1.4

[a] Upper boundary on installed capacity is saturated.

hydropower share on the overall electricity generation. The reduction is estimated by the presented full decarbonisation simulations in 13 percentage points (from 20 % to 7 %). Still, hydropower maintains a non-negligible role on the energy system configuration and operation.

In both the intermediate and full decarbonisation scenarios, the optimised operation of these systems significantly reduces the need for battery storage. In the net-zero systems, the BESS/IRES ratio diminishes by 5–15 % when introducing a system-optimised operation strategy for

HWR, except for the case with reference year 2020, which is instead supported by a high solar irradiance that fosters the capacity factor of PV. Similarly, the intermediate decarbonisation assessment shows that the optimal use of HWR systems eliminates the need for battery storage at same installed capacity of intermittent renewable power generation.

Hydropower is strongly dependent upon water availability (i.e., rainfalls). As the analyses on different reference years show, higher levels of precipitation enable an increase in hydroelectric power generation, leading to a reduction in the need for BESS as flexibility elements in the system. On the opposite, when assessing the 2050 scenario according to the reference year 2022, which features a very low inflow, a significant increase in BESS and PV installations is observed (around 30 % and 20 %, respectively) compared to the results for reference year 2019 (see Table 4). Even if these quantities do not drastically change the overall system, the deltas of installation are reasonably higher than current system capacities, showing that changing climatic conditions can vary the installation targets for achieving carbon neutrality.

Results prove that an optimised HWR operation offers greater flexibility to the system. In all cases, a different behaviour, compared to the historical one, has proven to be beneficial for the system. This generally leads to the installation of more wind and photovoltaic systems while simultaneously reducing BESS needs. In the net-zero assessments, these changes are in the order of 5/10 %, highlighting the impact of accurate modelling of HWR operation. It is also important to note the increasing role of hydropower as a seasonal storage and peak shaving technology, as highlighted in all investigated years.

The results suggest that in future scenarios where the Italian energy system will have a higher share of non-programmable renewable sources, a different use of hydropower resources could be beneficial. It should be noted that while this change is favourable for the system, it may not be optimal for individual operators. Therefore, regulatory modifications are necessary to support optimal hydro operation.

6. Conclusions

This study investigated the role of hydropower flexibility in future GHG emission-constrained energy systems, by detailing the representation of hydroelectric plants in terms of power and energy capacity and resource availability.

To perform the analysis, a comprehensive dataset of programmable hydropower plants (PHS and HWR) in Italy has been created and made available, collecting available open-source information. It provides a complete list of plants, including the nominal power and energy storage capacity, which is typically unavailable in existing databases. Data have been aggregated at the regional level (NUTS-2) to compute the natural inflow profiles of HWR and PHS systems.

The role of hydropower in two distinct decarbonisation scenarios was investigated using the OMNI-ES energy system model, which adopts regional resolution, hourly detail, and perfect-foresight approach, targeting Italy as spatial scale and featuring a multi-vector perspective. The two assessments represent a full decarbonisation configuration (2050) and an intermediate decarbonisation perspective (2030). The analysis compared a flexible-operation strategy, with optimised management of HWR plants, and an assigned-operation strategy, with HWR generation profiles based on historical data. The analysis was conducted using four different reference years to derive the input timeseries (inflow or assigned operation in the two strategies, respectively) in order to assess also the effect of different climatic conditions.

The results highlight a significantly different use of HWR plants, shifting from a baseload output to a peak-shaving behaviour. HWR are especially used to compensate lack of wind or solar resources, which dominate all the cases. The different HWR operation strategy influences both investigated decarbonisation scenarios, with more relevant changes in the intermediate perspective due to the lower IRES installed capacity. The different operation strategies introduce minimal changes in the overall system total annual cost, but yield variations in the order of 5–10 % in the installation of some other key technologies, such as PV, wind, and batteries. Moreover, the extra flexibility offered by the flexible hydroelectric operation gives space to reduce the need for other storage units and thermoelectric generation. This trend is well described by the BESS/IRES ratio, which points out the ability of the system to sustain higher RES installation with a similar amount of BESS.

Hydroelectric operation appears important also for seasonal storage. Results clearly show the need of the energy system to optimise the future HWR operation to enhance seasonal patterns. To guarantee this, the introduction of novel regulatory frameworks may be needed, as well as a change in the market regulation and remuneration so to foster the adoption of system-optimal strategies by the single operators.

The comparison of different reference years clearly shows that a drop in precipitations, as occurs in the weather year 2022, influence the optimisation yielding a higher installation of BESS and a larger BESS/IRES ratio. These increases are not negligible and highlight the relevance and impact of hydropower. Even if it is expected to cover a low share of total power generation (e.g., less than 10 % of overall demand in the fully decarbonised scenario), its contribution will play a critical role in providing a programmable RES technology. In this perspective, a key advantage is that the hydroelectric capacity is already installed, and an optimised operation could favourably vary the needs for other storage technologies.

In conclusions, the analysis shown in this work show that the presence and the operational strategy of hydropower plants has a relevant impact on the identification of optimal configurations of a decarbonised energy system. At the same time, uncertainty related to climatic conditions is not negligible. These elements suggest that system planning and policymaking should take into consideration the contribution of hydropower when studying future optimal energy system structure and regulations.

Further research to gain additional insights on this effect may include not only historical climatic conditions but also future projections, as well as examining the possible change in hydropower resources due to global warming.

CRediT authorship contribution statement

M. Catania: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **F. Parolin:** Writing – original draft, Validation, Software, Investigation, Data curation, Conceptualization. **F. Fattori:** Supervision, Methodology, Conceptualization. **P. Colbertaldo:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

Acronyms

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
DRI	Direct Reduction of Iron
EAF	Electric Arc Furnaces
EU	European Union
ESM	Energy System Model
ESR	Effort sharing regulation
ETS	Emission trading system
FCEV	Fuel Cell Electric Vehicle
FF55	Fit for 55
GDP	Gross Domestic Product
GHG	GreenHouse Gas
HVC	High Valuable Chemical
HWR	Hydro Water Reservoir
ICEV	Internal Combustion Engine Vehicle
IRES	Intermittent Renewable Energy Source
JRC	Joint Research Centre
LF	Liquid Fuels
NECP	National energy climate plan
OCGT	Open Cycle Gas Turbine
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES	Renewable Energy Sources
RoR	Run-of-River
SEV	Storage Energy Value
TSO	Transmission System Operator

Symbols

C	Electric energy storage capacity
C_{water}	Water volume of hydropower basins
$E_{HWR,j}$	Energy generated by hydro water reservoir plants at hour j
$E_{PHS_{gen},j}$	Energy generated by pumped hydro storage plants at hour j
$E_{PHS_{con},j}$	Energy consumed by pumped hydro storage plants at hour j
H	Head of a hydropower plant
$Inflow_i$	Inflow to hydropower plants (HWR and PHS) in week i on regional basis
SEV_i	Storage energy value of hydro water reservoir and pumped hydro storage plants in week i
$\widetilde{q}^{r,t}_{inflow,HWR}$	Inflow to hydro water reservoir plants in region r and time step t
$Q^{r,t}_{HWR}$	Storage content of hydro water reservoir plants in region r at time step t
$q^{r,t}_{otp,HWR}$	Power output of hydro water reservoir plants in region r at time step t
η	Energy conversion efficiency of hydropower plants

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