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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Energy modeling and Life Cycle Assessment of the Italian electricity grid and energy storage system: comparison of current state and forecast to 2030

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Abstract

Purpose The aim is to fill two literature gaps concerning the role of energy storage systems (ESS) in the future Italian electricity mix. Firstly, there is a lack of national-scale simulations for the energy performance of the Italian grid and ESS in a future-oriented scenario. Secondly, there is an absence of an integrated dynamic simulation model combining Life Cycle Assessment (LCA). The study specifically investigates whether ESS connected to grid infrastructure can provide environmental benefits at the national level, excluding behind-the-meter installations.

Methods The study introduces a method to comprehensively assess the joint energy and environmental performance of the electric grid and storage systems. A two-step model is used to simulate the Italian electricity grid, which employs the International Renewable Energy Agency (IRENA) Flextool software to model the national grid and a MATLAB code to evaluate the performance of ESSs. A LCA is performed in order to evaluate the potential environmental impacts of the whole system, including the power generation and storage facilities deployed at national level. The Life Cycle Inventory covers different storage systems, such as Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NCM) batteries, Pumped Hydro Storage (PHS), and Hydrogen Storage Systems (HSS).

Results and discussion The findings underscore that the achievement of the goals of the Integrated National Energy and Climate Plan (INECP) incorporating ESSs can significantly diminish electricity production from fossil fuels, leading to reduced greenhouse gas emissions. However, the study notes that existing ESS capacities are inadequate to fully harness excess energy. To address this, the proposal includes deploying more extensive storage capacities across Italy and embracing power-to-x solutions. Despite minimal environmental impact from ESSs compared to the entire grid, storing surplus electricity from renewables offers substantial environmental benefits. The research emphasizes the substantial resource and environmental impact of PV systems during the construction phase.

Conclusion This study reveals that, while the INECP aligns with greenhouse gas mitigation goals, there are environmental concerns like critical material consumption. Additionally, the impact of a national grid-level ESS may be limited in smoothing demand and generation curves, especially compared to smaller utilities. Despite being recognized as vital for energy transition, particularly in distributed behind-the-meter applications, grid-connected ESSs have a marginal impact on significantly reducing the overall environmental footprint of the electric generation mix.

Keywords Italian electricity grid · Energy modeling · Life Cycle Assessment · Energy storage systems

Nomenclature

AWE	Alkaline water electrolyzer
CDE	Charge-discharge efficiency
CC	Climate change
EBS	Electric battery systems
ED	Electricity demand
EoL	End-of-life
ESSs	Energy storage systems
EF	Environmental footprint
FC	Fuel cell
GHG	Greenhouse gas
HD	High demand
HSS	Hydrogen storage system
INECP	Integrated National Energy and Climate Plan

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IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFP	Lithium iron phosphate
LD	Low demand
MD	Medium demand
NCM	Nickel manganese cobalt
PV	Photovoltaic
PEMFC	Polymer electrolyte membrane
PR	Power rating
PHS	Pumped hydro system
RES	Renewable energy source
Rumm	Resource use, minerals and metals
VRES	Variable renewable energy sources

1 Introduction

Continued massive greenhouse gas (GHG) emissions into the atmosphere are leading to a steady rise in global temperatures with drastic effects on our planet. Immediate actions are needed to achieve the goal of keeping the average temperature increase below 1.5 °C by 2050 (IPCC 2018). European policies are intensively driving toward the goal of climate neutrality and a net-zero economy by 2050 (European Commission 2018). The sources of GHG emissions can be several: energy, industry, mobility, buildings, and others. In particular, the energy sector has a significant impact on global GHG emissions since energy systems released about 33 Gt of carbon dioxide into the atmosphere in 2021; this value represents about 75.00% of European GHG emissions (European Commission 2020) and is about 60.00% higher than the amount emitted in 1990 (IEA 2021). At the European scale, despite the decarbonization efforts in recent years, the energy industry (public electricity and heat production, petroleum refining, manufacturing industries and construction, fugitive emissions from fuels) still remains the main contributor to annual GHG emissions, representing about 25.96% of the total net emissions (EEA 2021). Many European countries are addressing this issue by planning policies and programs for the energy transition. With this perspective, governments are decarbonizing the way of generating and distributing energy by setting very ambitious energy transition targets (Bundesamt für Energie 2020, Bundesgesetzblatt 2021, Government of the French Republic 2020, Government of Italy 2019, Danish Ministry of Climate Energy and Utilities 2019, Government of Spain 2020, Republic of Slovenia 2020). The strategy implemented by most European countries is to cover the electric load by increasing the penetration of variable renewable energy sources (VRES), thus replacing current power generation plants with alternative technologies such as photovoltaic (PV) and wind. In such a context, increasing the flexibility of the national electricity system, which is the ability of the electrical grids to handle demand and generation system variability and uncertainty (Heggarty et al. 2020), becomes a topic of great interest for utilities (Kaushik et al. 2022). Indeed, VRES systems are very climate-dependent, and they may not be sufficiently productive to fulfill energy demand constantly. However, energy storage systems (ESSs) (Denholm et al. 2010; McPherson et al. 2018) can extend the capacity of VRES to provide continuous energy supply to the grid. For these reasons, ESSs are expected to play a key role in a green energy transition. Nevertheless, as demonstrated by the following literature review, the amount of storage systems that would be necessary to achieve the ambitious goals of the Green New Deal depends on the geographical context and is still uncertain. Furthermore, different types of ESS (e.g., chemical, electrochemical, electrical, mechanical, and thermal) are available and have different characteristics (Guney and Tepe 2017). Finally, ESSs can be installed at the national grid level or by consumer households behind-the-meter.

A literature review indicates that electrical systems with high VRES penetration require an extremely large installed capacity of ESS to maintain system balance (Jensen and Greiner 2014). The ratio between the rated power of the installed storage facility and the percentage contribution of VRES to the national energy mix in Europe is defined in Cebulla et al. (2018). However, this value is influenced by the availability of VRES (e.g., the intensity and temporal distribution of solar radiation), which depends on country-specific meteorological conditions, as well as on the technical characteristics of ESSs and the deployment of VRES technologies (e.g., PV, wind).

For instance, short-term ESSs, such as batteries, are optimal for supporting a high-capacity solar system because they can be charged and discharged in a few hours. Medium-term ESSs, such as pumped hydro, are optimized in cases where the grid connection is well distributed since they rely heavily on geographic features. Long-term ESSs, such as hydrogen systems, enable improved seasonal storage and often become necessary to compensate for the stochastic fluctuations in wind power generation (Bussar 2014).

A close relationship exists between storage and system balancing, particularly the combination of short-term storage technologies, which have high efficiencies, and long-term ESSs, which have low efficiencies. For this reason, diversification of storage technologies deployed at the national level would contribute to addressing this issue: a hybrid and distributed portfolio of ESSs composed of different short-, medium-, and long-term technologies has a higher overall roundtrip efficiency than single-technology solutions, also extending the capacity of maintaining the system's balance (Rasmussen et al. 2012).

In several countries, the most suitable mix of storage technologies to be deployed depending on country-specific conditions has not yet been clearly identified (Thimet and Mavromatidis 2022). In Italy, a few scenarios are available according to the Integrated National Energy and Climate Plan (INECP). However, dynamic simulation of the electric grid and a Life Cycle Assessment (LCA) are necessary to ensure that the energy storage solutions proposed by the INECP are technically and environmentally advantageous, considering the ever-increasing deployment of VRES technologies.

In Italy, several studies have been conducted to examine the environmental impacts of the electricity production mix. Gargiulo et al. (2020) utilized Life Cycle Assessment (LCA) to analyze three scenarios of the Italian electricity system projected to 2030. Their study highlights the contributions of different electricity generation systems to the total environmental impacts of the energy mix and compares them with two reference scenarios from 2016 and 2017 respectively (Gargiulo et al. 2020). Carvalho et al. (2022) employed a similar approach to compare the future and current Italian electricity mix, specifically in 2018 and 2030. The authors also conducted a comparison with other European countries and their energy programs (Carvalho et al. 2022).

In the aforementioned studies, the contribution of ESS is not included in the environmental assessment of the future energy production mix nor are the impact mitigation effects of storage technologies. In contrast, there are several studies concerning the LCA of behind-the-meter ESS. This type of study was conducted at the local level by Gandiglio et al. (2022), who performed an LCA analysis of a village located on an Italian island by comparing the current diesel-based electrical system with a renewable energy source (RES)-based system coupled with a hybrid hydrogen-battery storage system (Gandiglio et al. 2022). On the other hand, Cellura et al. (2019) carried out an LCA at the regional level, considering one Italian region (Sicily), and comparing the electricity system in 2014 with two forecast scenarios projected to 2030.

Finally, Rossi et al. conducted the eco-design of local microgrids by integrating LCA with dynamic simulation models (Rossi et al. 2020a, 2020b), mathematical optimization, and life cycle costing (Rossi et al. 2020c, 2021).

From the review outlined in the previous paragraphs, two major literature gaps can be identified. Firstly, according to the authors' knowledge, the energy performance of the Italian grid and ESS in a future-oriented scenario have not been simulated at the national scale. Secondly, an integrated dynamic simulation model of the Italian energy system has never been combined with Life Cycle Assessment (LCA) to focus on the environmental contribution of ESSs in the national energy mix (including benefits and impacts). Indeed, except for a few analyses at the local scale, the environmental benefits potentially resulting in the future from ESS in the entire Italian electric system are not yet clear. In particular, no existing studies have conducted national-scale simulations that explicitly incorporate the interaction between ESSs and grid flexibility dynamics from an environmental point of view. For this reason, the approach developed in this study is specifically designed to fill this research gap in the current literature.

The objective of this paper is to investigate the abovementioned literature gaps concerning the role and more specifically the environmental impact of ESSs in the future Italian electricity mix using a scenario-based approach through LCA. In particular, while the potential advantages of behind-the-meter installations have already been analyzed in previous works, this study investigates whether ESSs connected to the grid infrastructure can also provide environmental benefits to the Italian national energy mix. For this reason, behind-the-meter installations were not considered, and only national grid-level systems were analyzed. The aim is to develop a generalized approach that can serve as a foundation for future studies on energy systems integrating renewable sources and storage technologies, both at national and sub-national scales. It should be noted, however, that the current implementation is limited to a national scale and does not include any economic evaluation, which could be addressed in future research to enhance the comprehensiveness of the analysis.

2 Methodology

The approach used in this study is designed to conduct two different but interconnected analyses: (i) the dynamic simulation of the national electricity grid and (ii) a prospective scenario-based Life Cycle Assessment (LCA) model of the Italian electric grid. The second analysis requires inputs from the first one, specifically the energy flows exchanged by the grid. Consequently, an environmental assessment is conducted to calculate the environmental burdens of the future Italian electricity generation mix, with a focus on the contribution of ESSs. The following subsections provide a description of the energy system simulation (Section "Electricity grid modeling") and the LCA model developed in this study (Section "Environmental analysis").

2.1 Electricity grid modeling

The electricity grid model, schematically represented in Fig. 1, is divided in two steps (Fig. 1):

- *Step 1*—a simulation model of the Italian electricity grid without ESS is performed using an open-source software called IRENA Flextool (IRENA 2018);

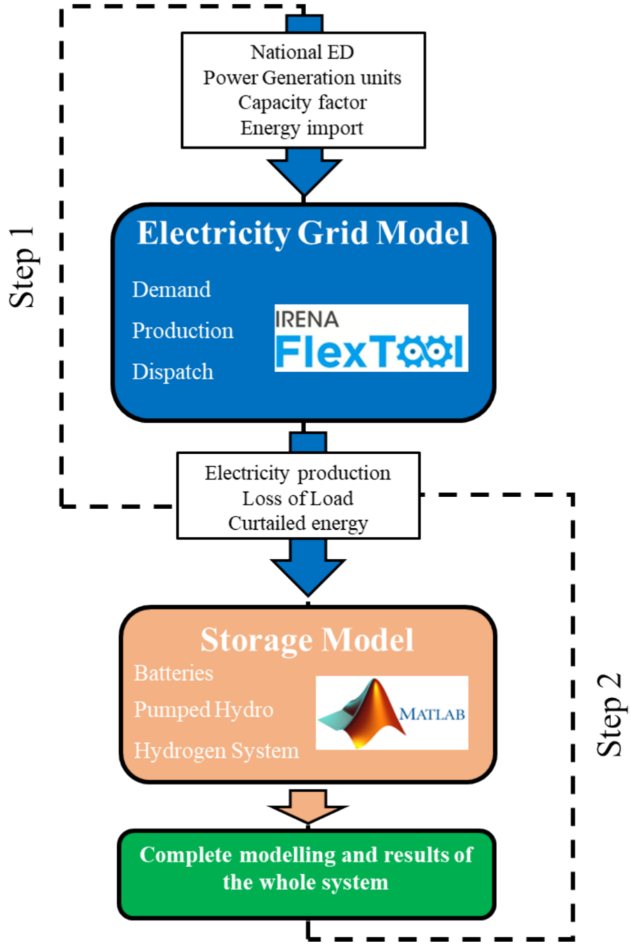

Fig. 1 Block diagram of the methodology used for modelling the electricity system and storage systems

- *Step 2*—an internally built model, relying on a MATLAB code, recalculates the results obtained in *Step 1* considering the ESSs performance.

The first part of the study involves the energy modeling of the Italian electricity grid, utilizing the simulation tool developed by the International Renewable Energy Agency (IRENA). This tool enables the determination of the behavior of the electric grid with high temporal resolution (1 h), allowing for the evaluation of the contribution of all energy sources to supply the national energy demand on an annual basis (IRENA (2018). Additional specific details can be found in the software manual (Taibi et al. 2019).

According to the software's structure, a grid can be modeled as the connection of multiple nodes, where each node represents an exchange point for electricity with a load, a power generation unit, a storage facility, or neighboring countries. However, since spatial dislocations throughout the Italian territory are not considered, the proposed model simplifies the grid into two nodes: (i) one node aggregates Italian electricity generation and consumption and (ii) one node aggregates electricity imports from neighboring countries. The generation units considered in the first node include fossil, biomass, geothermal, hydroelectric, wind, and photovoltaic sources. The simulation time is set to 1 year, with a simulation timestep of 1 h. This model operates as a black box, relying on the following inputs:

- The national electricity demand (ED) evaluated as a hourly-based profile.
- Size of power generation units, in terms of installed capacity (MW).
- Capacity factor and productivity coefficients power generation systems (including wind, PV, and other generation sources separately).
- The annual electricity imports from neighbor countries (in terms of amount of energy MWh/year).

The Irena Flextool returns the electricity flows exchanged between the grid, the power generation units, and the imports from other countries and several other outputs. However, this work only focuses on those results that represent useful as inputs for the following steps:

- Electrical energy produced by each source evaluated per hour, $E_{P,i}$ (*i*: fossil, biomass, geothermal, photovoltaic, wind, hydro).
- Loss of load, defined as the amount of energy lacking from the system to meet demand (the difference between ED and $E_{p,TOT} = \Sigma E_{p,i}$, in case that $E_{p,TOT} < ED$).
- Curtailed energy, defined as the amount of energy overproduced by the system compared to ED that is not made useful to users (the difference between $E_{p,TOT,}$ and ED in case that $E_{p,TOT} > ED$). In other words, this term could be also considered as a waste energy flow.

It is important to emphasize that, at step 1, all the outputs summarized in the above bullet point list are evaluated without considering ESSs, which would be useful for accumulating curtailed energy and re-injecting it afterwards (as occurring in step 2) to compensate for loss of loads or to increase the penetration of VRES.

The output tables generated by the IrenaFlextool are utilized as inputs for the code implementing the energy balance of ESSs. The ESSs that have been used are the most widely used types (Denholm et al. 2010; McPherson et al. 2018), and the proposed operating model is a simplified one. The storage systems considered by the model include the electric battery systems (EBS), pumped hydro systems (PHS), and hydrogen storage systems (HSS). The energy performance of EBS, PHS, and HSS depends on two specific parameters:

- Charge–discharge efficiency (CDE), defined as the product of charge and discharge efficiency.
- Power rating (PR), defined as the amount of energy that the ESS can feed into the system in one hour.

The CDE (charge–discharge efficiency) is a parameter that depends on the characteristics of each storage technology. For EBS, the PR (roundtrip efficiency) was assumed to be equal to half its maximum charge, as the discharge time of a battery can be very fast. Their CDE was assumed to be 90.00% (Taibi et al. 2019). Pumped hydro systems (PHS), on the other hand, typically have long discharge times; therefore, the nominal PR was assumed to be 20.00% of the maximum charge. In this case, the discharge efficiency, when the water level drops, is 85.00%, while the charging efficiency, when the water level rises, is assumed to be 90.00%, resulting in a total CDE value of 75.00% (Abdi et al. 2017). Hydrogen storage systems (HSS) are composed of several sub-units: (i) a water electrolyzer (WE) electrochemically converts electricity into hydrogen; (ii) hydrogen is compressed and accumulated in pressurized tanks (H2 Tank); (iii) then, fuel cells (FC) convert hydrogen into electricity through an electrochemical reaction. Since all the steps of the conversion systems result in a certain loss of energy, the CDE of this system is quite low and is assumed to be 35.00% (Armaroli and Balzani 2011); PR was assessed as a function of the FC treatable flow rate, and the tank storable volume is equal to half the storable capacity. The logic of the energy system modeling implemented in the Matlab code is as follows:

- the ESS is charged when the energy curtailment due to the overproduction of VRES is greater than zero; therefore, the Curtailed energy evaluated by Irena Flextool is re-calculated in MATLAB code, considering the energy balance of ESSs;
- the ESSs is discharged when the ESS delivers electricity to the grid; ESSs can be used primarily to compensate Losses of load, or eventually to reduce the consumption of fossil fuels. Hence, the MATLAB code re-calculates the energy losses and the electricity throughput of Fossil power plants by solving the energy balance of the ESS.

In both cases indicated in the bullet point list, the ability to charge and discharge ESSs is constrained by the charge level of the systems and the maximum capacity of ESSs. Consequently, the charge level of ESSs is dynamically calculated at every time step: if the ESSs' capacity is full, the storage system cannot be recharged, and the excess energy is wasted; if it is empty, ESSs cannot be further discharged, resulting in a loss of load.

For a clearer understanding of the MATLAB model, the code logic is depicted in Fig. 2 in the form of a block diagram. Figure 2 illustrates the outputs of IrenaFlextool as B

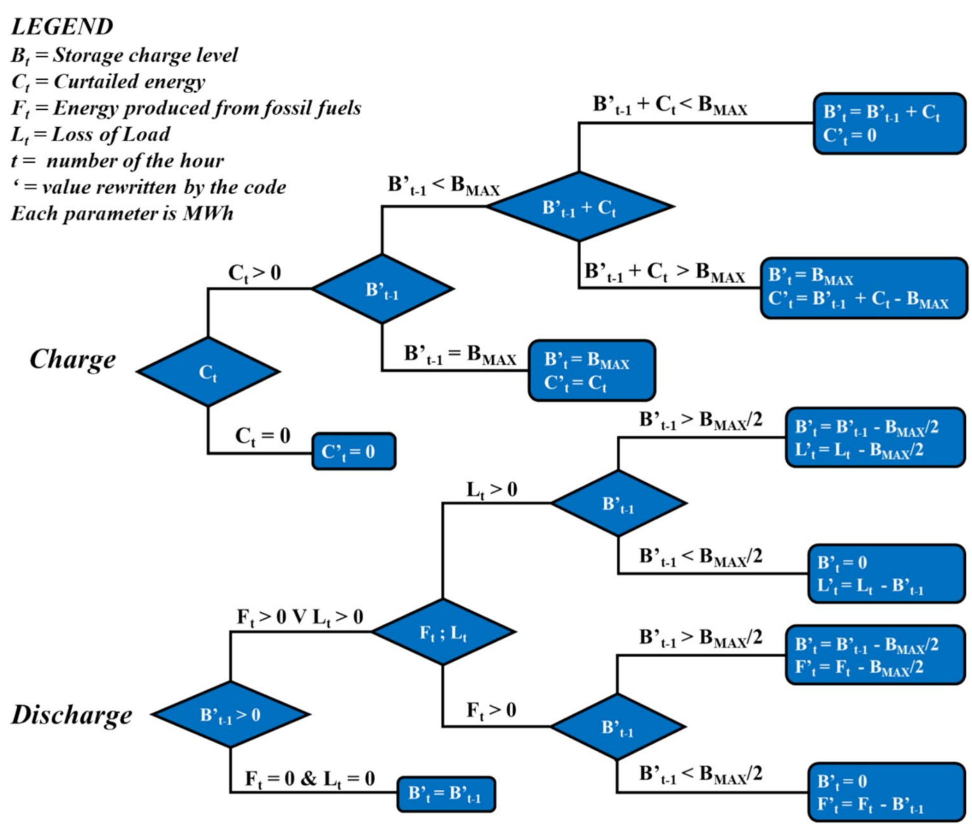

Fig. 2 Block diagram for storage operation code

(storage charge level), C (energy curtailed), F (energy produced from fossil fuels), and L (loss of load); conversely, B', C', F', and L' represent the same variables recalculated in MATLAB considering the energy balance of ESSs.

2.2 Environmental analysis

The potential environmental impacts of the future Italian electricity generation system in the multiple scenarios are estimated from a life cycle perspective. The applied methodology follows the standardized LCA proposed by ISO 14040 and ISO 14044 (ISO 2021a; ISO 2021b). The adopted LCA approach is attributional, which describes environmentally relevant physical flows to and from the environment over life cycle of the product system (Finnveden and Potting 2014). The open-source software OpenLCA version 2.4 with the Ecoinvent 3.10 (FitzGerald et al. 2023) database was used for the calculations. The LCA model is developed to examine different scenarios, extensively discussed in Section "Case Study Definition", differing for the amount of electricity produced from each energy source and the electricity demand by energy users.

2.2.1 Goal and scope definition

The aim of the study is to investigate the environmental impacts arising from the electrical system and ESS in 2030, with a particular focus on assessing the environmental impact of grid-connected storage facilities and the benefits derived from them. The life cycle modeling approach for ESS is cradle to grave, encompassing the construction, operation, and end-of-life (EoL) phases. However, the electricity distribution infrastructure is not considered within the system boundaries. Additionally, due to the absence of spatial dislocation considerations of energy systems throughout the Italian territory, the transportation of ESS from production to installation sites is not included within the system boundaries.

The life cycle phases included in the boundaries are modeled using foreground and background processes, as discussed in more detail in Section "Life Cycle Inventory". The functional unit is defined as the electrical energy delivered to consumers, represented by the electrical MWh fulfilling the utilities' demand.

2.2.2 Life cycle inventory

The national electricity system is modeled as the aggregation of simple energy flows generated by Italian power plants. The Ecoinvent 3.10 database provided data on the national energy mix: "Electricity production, high voltage, National energy mix, Italy." The different production sources were identified by grouping them into the same classes used in the modeling of the electrical system with Irena Flextool: Fossil, Hydro, Geothermal, Biomass, and Wind. Thus, the results of the grid simulation model described in Section "Electricity grid modeling" can be used as inputs for the LCA model.

However, each of the aforementioned groups contains sub-groups. For example, within the fossil category, different fuels (such as coal, oil, natural gas) and technologies (such as combined cycles and steam power cycles) are available for electricity production. To ensure an accurate model considering all electricity production pathways, the proportions proposed by Ecoinvent are maintained to determine the contribution of each sub-group. Similar considerations apply to different PV systems, assumed to be connected to the low voltage grid, and to the mix of electricity imported from foreign countries (Slovenia, Switzerland, France, Austria, and Greece). Below is a summary table of the selected providers (Table 1).

Regarding the Life Cycle Inventory (LCI) of the storage systems, secondary data obtained from various literature sources have been utilized as reference.

The EBS pack is modeled as a combination of Lithium Iron Phosphate (LFP) batteries (50.00% of the overall batteries capacity) and nickel manganese cobalt (NCM) batteries (50.00% of the overall batteries capacity). LFP batteries have an energy density of 109.3 Wh/kg, while NCM batteries have an energy density of 139.1 Wh/kg (Peters and Weil 2018). An End-of-Life (EoL) model is implemented, taking into account mechanical dismantling and recycling processes; specifically, it is assumed that 50.00% of the batteries undergo hydrometallurgical treatment, while the other 50.00% undergo pyrometallurgical treatment (Weber et al. 2018). The useful life of the EBS pack is estimated to be 15 years.

The Life Cycle Inventory (LCI) of a Pumped Hydro System (PHS) comprises several elements: an upstream and downstream basin, an intake structure, piezometric well, pipelines, turbine/pump-alternator unit, and delivery cabin. Additionally, the excavation and site preparation phases, as well as operation and maintenance, are considered (Kjølle 2001; Miu 2016). The EoL phase includes the disposal of the turbine and the steel that compose the surface pipelines (Torres 2011). The useful life of PHS varies widely and can range from 50 to 100 years; in this case, it has been estimated at 60 years (Moreau et al. 2012).

The hydrogen storage system (HSS) comprises four functional sections: electrolyzer, compressor, tanks, and fuel cell. Among various types of electrolyzers available in the market, the study considers Alkaline Water Electrolyser (AWE) (Lotrič et al. 2021). A compressor is used to pressurize hydrogen with a non-constant flow rate of up to 500 bar. Gaseous hydrogen produced by electrolyzers is stored in large tanks capable of storing approximately 300 L of gas

Table 1 Italian energy mix provider in Ecoinvent 3.10

Electricity production, high voltage, national energy mix, Italy	Classes
Electricity production, oil | electricity, high voltage | cutoff, S – IT	Fossil – oil
Heat and power co-generation, oil | electricity, high voltage | cutoff, S – IT	
Electricity production, lignite | electricity, high voltage | cutoff, S – IT	Fossil – coal
Electricity production, hard coal | electricity, high voltage | cutoff, S – IT	
Treatment of blast furnace gas, in power plant | electricity, high voltage | cutoff, S – IT	
Heat and power co-generation, hard coal | electricity, high voltage | cutoff, S – IT	
Treatment of coal gas, in power plant | electricity, high voltage | cutoff, S – IT	Fossil – gas
Electricity production, natural gas, combined cycle power plant | electricity, high voltage | cutoff, S – IT	
Heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical | electricity, high voltage | cutoff, S – IT	
Electricity production, natural gas, conventional power plant | electricity, high voltage | cutoff, S – IT	
Heat and power co-generation, natural gas, conventional power plant, 100 MW electrical | electricity, high voltage | cutoff, S – IT	
Electricity production, hydro, pumped storage | electricity, high voltage | cutoff, S – IT	Hydroelectric
Electricity production, hydro, reservoir, alpine region | electricity, high voltage | cutoff, S – IT	
Electricity production, hydro, run-of-river | electricity, high voltage | cutoff, S – IT	
Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | electricity, high voltage | cutoff, S – IT	Biomass
Heat and power co-generation, biogas, gas engine | electricity, high voltage | cutoff, S – IT	
Electricity production, deep geothermal | electricity, high voltage | cutoff, S – IT	Geothermal
Electricity production, wind, <1 MW turbine, onshore | electricity, high voltage | cutoff, S – IT	Wind
Electricity production, wind, >3 MW turbine, onshore | electricity, high voltage | cutoff, S – IT	
Electricity production, wind, 1–3 MW turbine, onshore | electricity, high voltage | cutoff, S – IT	
Electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | cutoff, S	Photovoltaic
Electricity, high voltage, import from GR | electricity, high voltage | cutoff, S – IT	Import
Electricity, high voltage, import from FR | electricity, high voltage | cutoff, S – IT	
Electricity, high voltage, import from SI | electricity, high voltage | cutoff, S – IT	
Electricity, high voltage, import from AT | electricity, high voltage | cutoff, S – IT	
Electricity, high voltage, import from CH | electricity, high voltage | cutoff, S – IT	

(equivalent to around 9.5 kg) at 500 bar. The approach used involved linearly scaling the tank IV type as reference inventories (Agostini et al. 2018) based on pressure as the dimensioning quantity. The fuel cell model is based on polymer electrolyte membrane technology (PEMFC), with its inventory data available in the literature (Valente et al. 2019).

During the operation phase, electricity consumption by the compressor and the deionized water consumed by AWE are accounted for. Maintenance involves the replacement of degraded materials in the PEMFC. It is noteworthy that hydrogen consumption cannot be solely attributed to electrical purposes; hydrogen serves various functions such as transportation fuel and as a reactant in the chemical industry. Therefore, only a fraction of the AWE installed in the future Italian energy system is allocated to power generation.

The end-of-life (EoL) phase is modeled to include the recovery of raw materials, recycling, and disposal for both AWE and PEMFC (Lotrič et al. 2021). The estimated useful life of the HSS is approximately 10 years (Agostini et al. 2018). Given the differing useful life values among the technologies analyzed, the longest one, PHS, serves as the reference, and the other two systems are adjusted accordingly to this time scale (60 years). The complete model inventories are provided in the supplementary materials.

2.2.3 Life cycle impact assessment method

The methodology proposed by European Commission called Environmental footprint 3.1 (EF) (Fazio et al. 2018a) was used in this study. The methodology has 16 categories evaluated at midpoint level, which refer to multiple environmental issues Among them, two impact categories were selected to give a representative picture of the case study, which are discussed in detail:

- *Climate change* is an environmental indicator that measures the direct and undirect amount of GHG emitted over the life cycle of the system and it is expressed as kg of CO_2 equivalent emission according to the EF guidance. This indicator is selected because it is the most widely used in LCA studies.

- *Resource use, minerals, and metals* is the environmental indicator developed on the model of Abiotic Depletion Potential for mineral and metal resources, based on van Oers et al. (2002). It is calculated as kg of Sb equivalent and it represents the direct and indirect consumption of minerals and metals occurring over the life cycle of a product.

Moreover, the single score indicator can be evaluated, according to EF3.1 guidelines (European Commission, Directorate-General for Environment 2021), through the normalization and weighting of midpoint impact categories. According the ISO 14,040 standard, normalization, and weighting is optional phases, because it could add uncertainty to the results and lead to conclusions focused on some categories rather than others, with respect to different weighing sets. Meanwhile the *Product Environmental Footprint* or *Organization Environmental Footprint* methods, the weighting phase is mandatory, because used in the proper sense, to compare different systems in absolute terms, it can give information on the general trend of the whole environmental indicators. For a complete vision, all environmental indicators are provided in supplementary material.

3 Case study definition

This paper is focused on the future Italian electrical production mix and aims to investigate the expected contribution of ESS to enhance the share of VRES within the Italian energy system, and to improve thus the environmental sustainability of the national generation mix. Therefore, it is necessary to design some representative scenarios of the future Italian energy systems. As remarked in the methodological section; three types of data are necessary as inputs of the model:

- Electricity demand (ED), defined as the electrical demand of the national loads covered by the system. (Terna Driving Energy 2022a)
- Power capacity, referred to the size in terms of MW installed for each type of production system (Terna Driving Energy 2022b)
- Electricity production, considered as the net electricity supplied to consumers in MWh (Terna Driving Energy, n.d)
- Electricity imports from foreign countries in MWh.

Concerning the ED in 2030, it should be considered that future energy consumption may differ greatly compared to 2020 depending on several factors (e.g., electric mobility). For this reason, three different ED forecasts were taken as reference for each scenario to 2030. These forecasts reflect the possibility of having an increase, a near-constant level, and a decrease:

1) European green revolution – high demand (HD), developed by ENTSO-E with a top-down approach (Enstog and Entos-e 2020; Terna Driving Energy 2017).
2) Constrained progress – medium demand (MD), developed by ENTSO-E with a top-down approach (Enstog and Entos-e 2020; Terna Driving Energy 2017).
3) National green transition – low demand (LD) (Enstog and Entos-e 2020; Terna Driving Energy 2017).

Regarding the power capacity, the nominal installed power of PV and wind is calculated based on current values (as of 2020). According to INECP, the overall power of PV and wind systems expected to be installed in Italy by 2030 will increase by + 240.00% and + 170.00%, respectively. The size of hydropower remains nearly unchanged, with an increase of + 0.50%, while geothermal power increases by + 16.28%. Additionally, the share of biomass in the national electricity generation mix is expected to decrease by about − 8.43%, while the power of thermoelectric power plants in 2030 is projected to continue declining slightly, as it has already between 2017 and 2022 (− 0.67%). The energy produced from each source can be found in Section "Results".

Italy's electricity production system still heavily relies on power generation from conventional thermoelectric plants that consume fossil fuels, covering approximately 57.00% of electricity demand (ED). As of 2020, the penetration of VRES does not exceed 40.00%; particularly, PV and wind currently cover only 8.00% and 6.00% of the national electricity consumption mix, respectively. By 2030, with the additional installation of VRES systems, their contribution to the energy mix is expected to change significantly compared to the reference scenario. Electricity imports from neighboring countries typically represent a constant percentage of the annual ED, approximately 5.00%. Three scenarios are designed to highlight how the eco-profile of the electricity mix can change if storage systems are included in the system boundaries of the energy production mix. Initially, the study considers scenarios where ESSs are not accounted for in the energy production mix, as assumed in Energy and Terna Driving Energy (2022a). Subsequently, scenarios are created that include storage within the system boundaries. Analyzing scenario A is akin to skipping step 2 of the grid simulation model, which provides the LCA model with energy flows calculated by the Irena Flextool (which does not consider the presence of ESS). Conversely, in scenario B, both steps of the electricity grid model are considered to evaluate the energy behavior of ESSs. The contribution of storage to the LCA impacts can be calculated by the difference. A graphical representation illustrating how the definition of two future scenarios can highlight the role of storage is presented in Fig. 3:

For each scenario, three sub-scenarios are designed, which differ for the expected ED in 2030. The scenarios are detailed in the following bullet points:

- *Baseline scenario*: Italian electricity mix (2020), in which storage is not included within the system boundaries (Terna Driving Energy 2022b), is considered as a baseline for comparison.
- *Scenario A:* the future Italian electricity mix (2030) is considered without including storage Government of Italy 2019) neither in the simulation model nor in the system boundaries of the LCA study.
    - o *Scenario A.1*: the ED is low (LD)
    - o *Scenario A.2*: the ED is medium (MD)
    - o *Scenario A.3*: the ED is high (HD)
- *Scenario B:* the future Italian electricity mix (2030) is considered including storage (Government of Italy 2019) in the simulation model and in the system boundaries of the LCA study.
    - o *Scenario B.1*: the ED is low (LD)
    - o *Scenario B.2*: the ED is medium (MD)
    - o *Scenario B.3*: the ED is high (HD)

The abovementioned scenarios are designed to evaluate the effect of storage on the energy mix environmental sustainability, but also to address the uncertainty related to the future electrical demand. In the proposed scenarios, the overall capacity of the energy storage systems and the power of power generation units by source installed in Italy is set according to the scenarios proposed by INECP and is collected in Table 2.

4 Results

4.1 Energy analysis

In this section, the results of the electric grid energy modeling are presented; Fig. 4 shows three pie charts representing the Italian electricity production mix (including electricity imports from neighboring countries) calculated by IrenaFlextool. Since the percentage contribution of each source of energy is marginally affected by ED levels, it was chosen to focus the analysis on the intermediate case, the medium-demand future scenarios (*scenario A.2* and *scenario B.2*) (for graphs of all other scenarios, see Supplementary materials).

In *scenario A.2*, the portion of energy overproduced by VRE source is expressed as "curtailed" fraction that, without storage, is a waste energy stream. On the other hand, in

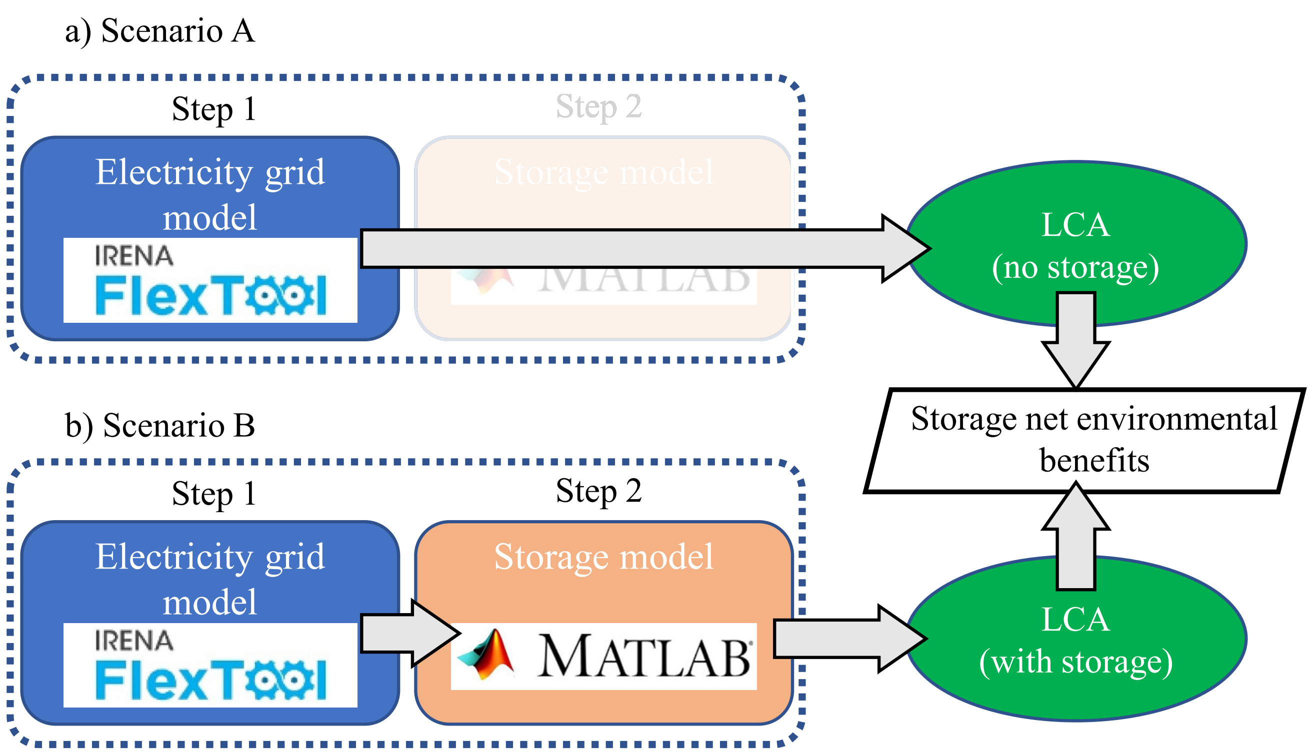

Fig. 3 Methodology block diagram

Table 2 Variable data for analyzed scenarios

	2020		Reference	2030		Reference
Demand TWh/y		301.18	Energy and "Terna Driving Energy 2022b	European green revolution	332.05	Terna Driving Energy 2017; T. D. E. Terna Group (n.d.); Terna Driving Energy 2022c
				Constrained progress	308.66	
				National green transition	290.89	
Capacity GW	Thermoelectric—fossil	58.90	Terna Driving Energy, n.d)	Thermoelectric—fossil	58.90	Government of Italy 2019
	Biomass	4.11		Biomass	3.76	
	Geothermal	0.82		Geothermal	0.95	
	Hydroelectric	19.11		Hydroelectric	19.2	
	Wind	10.91		Wind	19.3	
	Photovoltaic	21.65		Photovoltaic	52	
Storage GWh	EBS	[-]	Terna Driving Energy, n.d)	EBS	24	Government of Italy 2019; Ministry of Economic Development 2020
	PHS	3369[a]		PHS	6738	; Gerard, et al. 2020
	HSS	[-]		HSS	12.80	

[a]In the scenario 2020 model, the contribution made by pumped hydro is contained within the production from hydropower (installed capacity of 7328.5 MW and electrical output of 3369 GWh)

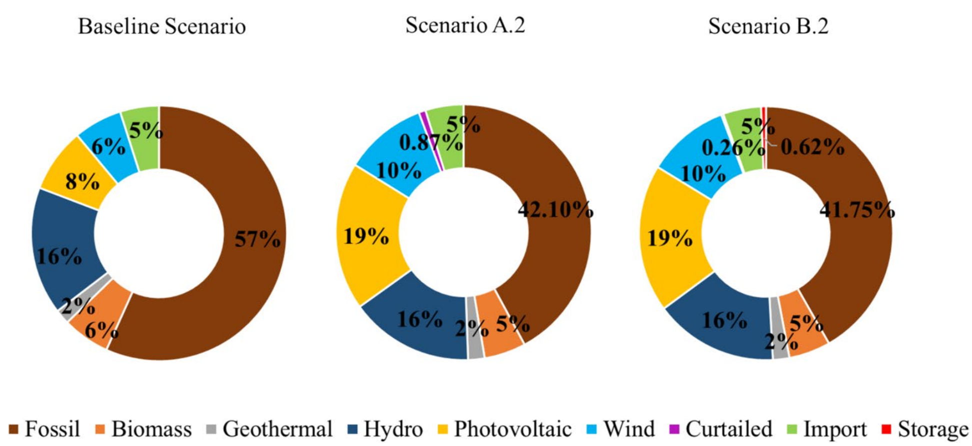

Fig. 4 Pie charts representing the share of energy supplied by each source under different scenarios

scenario B.2, ESS can accumulate the exceeding electricity produced from VRES and reinject it into the grid; this portion is called "storage," representing the energy stored by the ESS and made available to the electricity grid. Besides the presence of storage, *scenario B.2* also contains a term called "curtailed" energy since not all the energy surplus of the generation system is not reintegrated into the grid.

According to the results, in both *scenario A* and *scenario B*, the electricity generation system allows a complete fulfillment of ED because no load losses are detected by the model. The comparison between *baseline scenario* and *scenario A.2* shows a large percentage reduction of the electricity production from fossil fuels (approximately − 15.00%). At the same time, the penetration from RES is increased significantly, from 43.00 to 52.00%; this value is slightly lower than the target proposed by the INECP Government of Italy 2019) (i.e., 55.00%). Furthermore, it is evident that the amount of curtailed energy in *scenario A.2* is very low (only 0.87% of the electricity on the grid), so the potentially convertible useful energy represents a limited share. The pie chart of *scenario B.2* shows that the ESS only partially convert the curtailed energy into energy actually made available to users. In fact, ESSs can mitigate the waste of curtailed energy from 0.87% (*scenario B.2*) to 0.26% of the total electricity flowing through the grid, while 0.62% of the electricity remains curtailed.

To investigate the contribution of ESS to the electricity system as a function of the future national ED, a comparison among the *scenarios B.1*, *B.2*, and *B.3* is presented in Fig. 5. This chart highlights the fraction of the exceeding electricity overproduced by PV and Wind re-injected into the grid by ESSs, and the fraction of curtailed (thus wasted) energy. Figure 5 highlights that despite the reduction of curtailed energy, the size of the ESS is insufficient in all scenarios to transform the whole overproduction into useful energy. The range is between 63.00 and 76.00%; the remaining is anyhow curtailed, despite the presence of ESSs. However, from Fig. 5, it can be observed that the larger the increase of the national energy demand (scenario B.3), the lower the energy curtailment.

4.2 Environmental analysis

The environmental analysis is carried out using LCA methodology; a comparison of all scenarios for the impact categories *climate change* and *resource use, minerals and metals* is given below. For these two indicators, both a contribution analysis and a comparison between scenarios is made.

4.2.1 Climate change indicator

Figure 6 depicts the environmental impact of "climate change" resulting from the Italian electricity production mix categorized by source across various scenarios. According to the figure, in the baseline scenario, PV emissions contribute to 1.49% of the total. Conversely, in all future scenarios, PV's contribution is expected to increase, ranging between 3 and 4.5% of total GHG emissions. These indirect emissions associated with PV primarily stem from two processes: the construction phase of the PV module (70.00% of the impact) and the on-site assembly system (25.00% of the impact). On the contrary, wind systems in the baseline scenario have a minimal impact, contributing only 0.3% to the overall emissions. Other contributors, such as biomass, do not exceed 1.4% of total impacts. Additionally, imported energy from neighboring countries is shown to affect GHG emissions by 2%.

Regarding the prospective analysis of future scenarios, a comparison is made to investigate the GHG emission

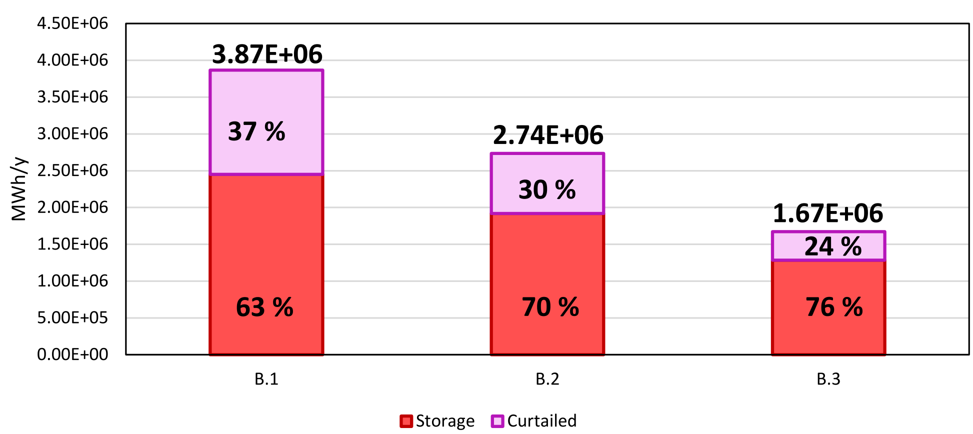

Fig. 5 Amount of curtailed energy by the system and energy fed into the grid by storage systems

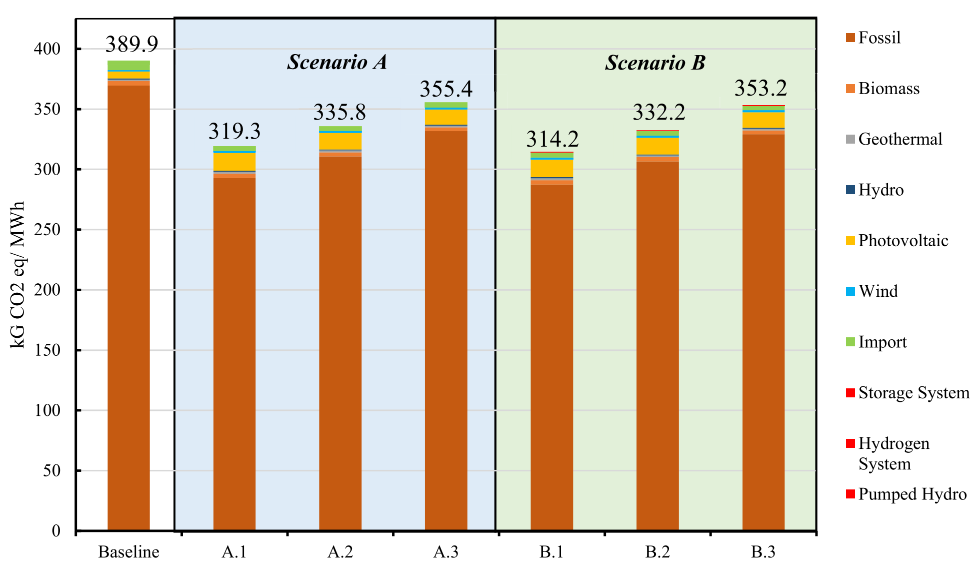

Fig. 6 Contribution analysis for the climate change category of all analyzed scenarios

mitigation resulting from the introduction of storage. Firstly, the discussion focuses on the medium ED case, which serves as a reference (A.2 and B.2). Then, the assessment is extended to low and high energy demand scenarios (A.1 and B.1, A.3 and B.3).

In Scenario A.2, it is projected that the Italian electricity mix in 2030 will still heavily rely on energy production from fossil resources, contributing to over 92% of the life cycle GHG emissions. The second most impactful contribution, albeit of a smaller magnitude, is the energy generated by PV plants. However, the results depicted in Fig. 6 indicate that, compared to the baseline scenario, the climate change indicator of the electricity mix in 2030 will significantly decrease from its 2018 levels. Specifically, without storage inclusion in the analysis (scenario A.2), the GHG emissions fraction in 2030 is expected to decrease from 396.53 kg CO2 eq/MWh (baseline scenario) to 335.8 kg CO_2/MWh (a reduction of 13.8%). Conversely, with storage considered (scenario B.2), the emission level of the national electricity grid mix is estimated at 332.2 kg CO_2 eq/MWh. Thus, the presence of storage enables avoiding an additional 3.7 kg CO_2 eq/MWh compared to scenario A2, equivalent to a further reduction of 0.9%. Moreover, the environmental burdens associated with ESSs in scenario A.2 are found to be significantly lower compared to other energy generation systems contributing to the production mix.

To address the uncertainty of future energy demand, scenarios A.1 and B.1, A.3 and B.3 are also evaluated. A broad observation of Fig. 6 reveals that the greater the increase in demand, the higher the impact on the electricity mix. This is evident as the rising electricity demand in Italy (observed transitioning from scenarios A1 to A3 and from B1 to B3) is met predominantly by fossil fuel-based power plants. Additionally, due to the heightened electricity demand, the overproduction of VRES systems (i.e., PV and wind) decreases along with the contribution of storage. This is illustrated by the comparison of the LD scenarios (A.1 and B.1), where storage enables a reduction of the climate change impact of the system by − 1.3%. Conversely, the GHG mitigation provided by storage between the HD scenarios (A.3 and B.3) is only − 0.6%.

4.2.2 Resource use, minerals, and metals indicator

Figure 7 provides a summary of the environmental impact of the Italian electricity production mix categorized under "resource use, minerals, and metals" across different selected scenarios. The analysis of this indicator, which pertains to

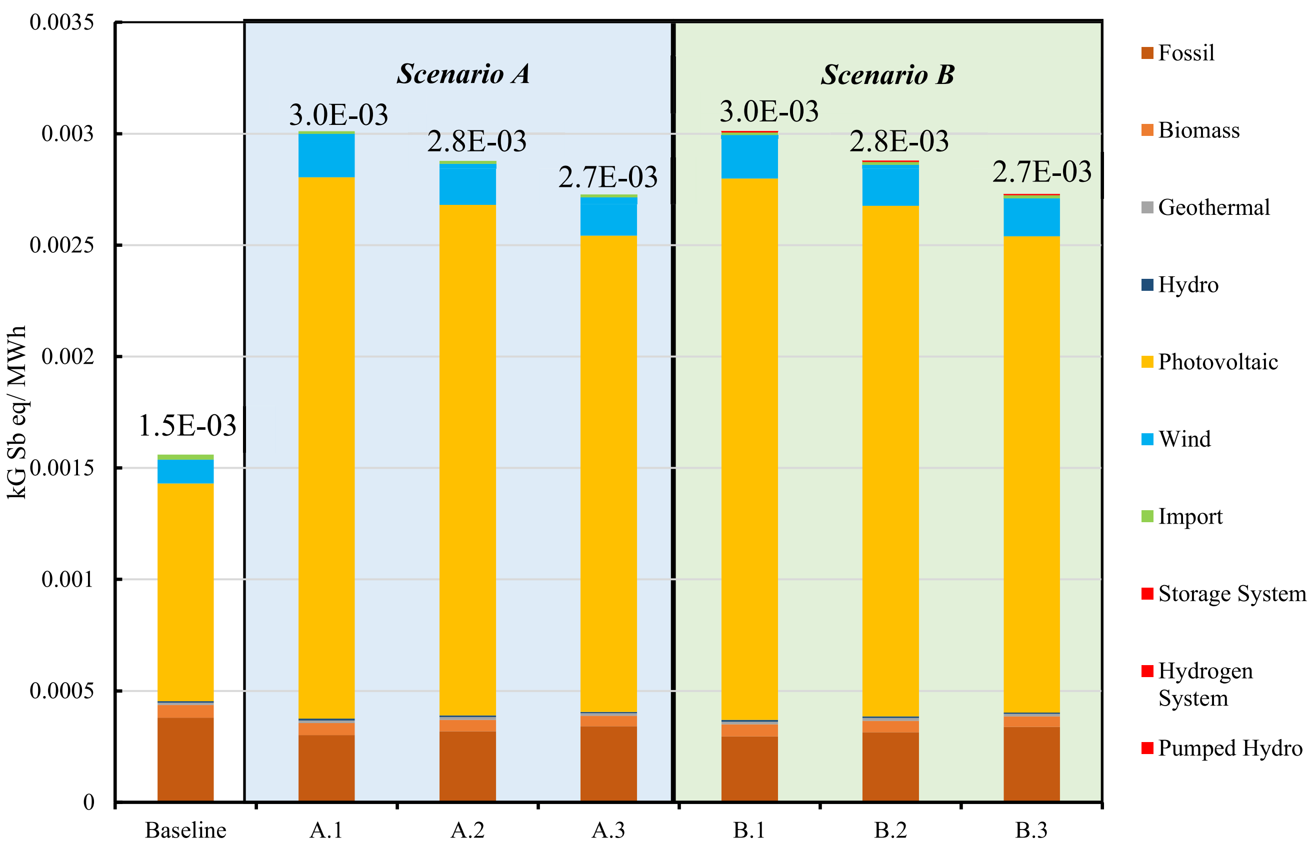

Fig. 7 Contribution analysis for the resource use, mineral and metal category of all analyzed scenarios

the consumption of mineral and metallic materials, reveals a distinct trend compared to GHG emissions.

In the baseline scenario, PV constitutes 62.6% of the total impact, representing the largest share. Fossil fuels follow with a contribution of 24.3%. Wind power exhibits a relatively low impact, accounting for approximately 6.8%, while other contributions remain below 5.00% of the total impact. To explore the consumption of mineral and metallic materials further, a comparison among the proposed scenarios is conducted. Similar to previous analyses, the intermediate energy demand case serves as a reference (A.2 and B.2). Additionally, the comparison is extended to low and high energy demand scenarios (A.1 and B.1, A.3 and B.3).

The findings depicted in Fig. 7 underscore that, in comparison to the baseline scenario, scenario A.2 projects a notable increase in the resource use, minerals, and metals (RUmm) indicator for the electricity mix in 2030. Specifically, the RUmm share rises from 1.56 g Sb eq/MWh to 2.87 g Sb/MWh, marking an 82.0% increase. Conversely, when storage is integrated into the analysis (scenario B.2), the overall system registers an emission of 2.86 g Sb eq/MWh, representing a marginal improvement for this impact category. Figure 7 illustrates that storage accounts for a negligible reduction within the context of the entire electricity generation system (0.16%).

The variability of future energy demand, as represented by scenarios A.1 and B.1, A.3 and B.3, is also incorporated into this evaluation. An overview of the histogram presented in Fig. 7 reveals that as the demand increases, the impact of the electricity mix decreases. This trend contrasts with the analysis conducted in the previous section. With an extension of electricity demand comes a heightened contribution from PV. Given that the impact category resource use, minerals, and metals is critical for solar energy technologies, an increased reliance on PV negatively affects this impact indicator. Comparing scenarios A and B, the contribution from photovoltaics remains consistent in terms of energy produced, comprising 81.0 to 79.0% of the total. Other contributions exhibit minimal changes in percentage terms and remain aligned with the values reported for the baseline scenario. Regarding the contribution of storage, similar observations apply for both low-ED (A.1 and B.1) and high-ED (A.3 and B.3) scenarios: the effect attributed to ESSs in this category is nearly negligible, with reductions less than 1.00% observed for both A.1 and B.1, as well as A.3 and B.3.

4.2.3 Single score analysis

The two former paragraphs demonstrate that, depending on the impact category, the impact of the energy production mix is extremely different. Therefore, this section introduces a single-score indicator that summarizes all environmental impact categories. The calculation was carried out with the normalization and weighting set provided by the OpenLCA software implementation of the Environmental Footprint methodology (Fazio, et al. 2018b; Sala et al. 2018). As a first step, the difference between the baseline scenario and the 2030 scenarios is highlighted, and then, specific comparisons are made considering the variability of ED in each scenario A and B. Figure 8 illustrates the single-score values for the baseline scenario (red bar); the blue bars represent the scenarios up to 2030 without ESSs (scenarios A), and the green bars represent the scenarios up to 2030 with ESS (scenarios B). The dotted green area represents the difference

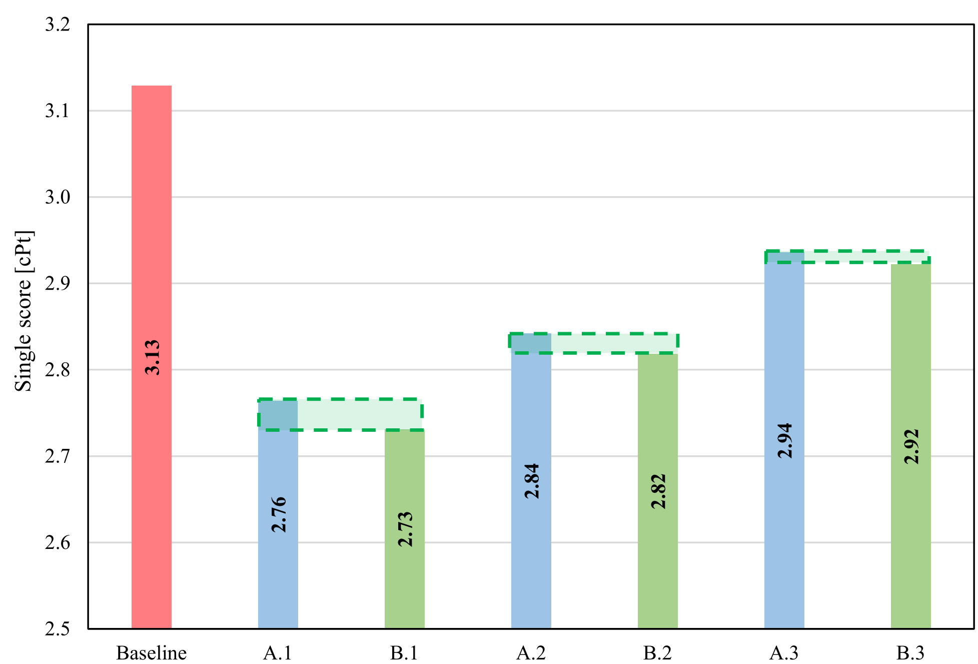

Fig. 8 Comparison of all scenarios at single score level

between scenarios A and B. This visual representation aids in comprehending the differences in environmental performance between scenarios with and without ESSs.

As shown in Fig. 8, the single score in the baseline scenario has a significantly higher value than in all scenarios: when comparing it with the reference case scenario A.2, it varies from 3.1 cPt/MWh to 2.8 cPt/MWh (− 9.2%). In scenario B.2, a marginal additional single score mitigation to 2.81 cPt/MWh is achieved. These findings underscore the relatively minor impact of ESSs on environmental performance, particularly when compared to the baseline scenario and so outcome confirms that the environmental benefits of grid-connected ESSs are very low. Similar considerations apply for all the scenarios with the same level of ED (A.1 and B.1, A.2 and B.2, A.3 and B.3): indeed, the reduction of impacts in terms of cPt/MWh determined by storage systems is not significant, as it turns out to be lower than 1.00%. This suggests that while ESSs may contribute to environmental mitigation, their overall impact remains marginal. Similarly, in the “climate change” category, the higher the ED, the higher the environmental burden due to the increasing contribution of fossil fuel power plants. This highlights the importance of considering the broader implications of energy generation and storage technologies on environmental sustainability, particularly in relation to reducing reliance on fossil fuels.

According to Fig. 8, the environmental impact of ESS compared to the power generation system is marginal. It can be explained as follows: the asynchrony between production and consumption, leading to energy storage into ESSs, is observed at national grid level, but it is considerably less remarkable compared to small utility and, even more, to single user level. This is due to the big consumers at national grid level, such as industrial, commercial, and service sectors’, which balance the daily and annual energy consumption and production. For this reason, energy storable by ESSs is extremely low (not exceeding 1.00% of the whole production), and therefore, the ESSs cannot significantly reduce the impacts resulting from the generation systems.

5 Conclusion

The present research paper addresses the crucial issue of assessing the impact of integrating large-scale energy storage systems (ESSs) at the national grid level, with the aim of evaluating their environmental contributions to electricity production. To achieve this objective, an integrated methodology combining energy grid modeling and Life Cycle Assessment (LCA) has been proposed.

The initial step involves calculating the annual energy exchange within the grid. This is carried out using a two-step approach: firstly, the energy modeling of the grid is performed using IRENA FlexTool, disregarding the presence of storage systems. Subsequently, a customized MATLAB code, tailored for this study, recalculates the energy exchange while considering the electrical behavior of ESSs.

In the second phase of the study, results from the grid energy modeling are used as inputs for an LCA model. This allows for the evaluation of the environmental impacts associated with the national electricity system through multiple indicators, including a final aggregation using the Single Score approach.

To assess the role of national-scale ESSs, three main scenarios were developed: the Baseline scenario (current energy mix), and two 2030 projections—Scenario A (without ESSs) and Scenario B (with ESSs). Each scenario was further subdivided into three sub-scenarios (low, intermediate, and high electricity demand: A.1–A.3, B.1–B.3), all aligned with INECP.

Grid modeling results indicate a renewable energy share of 55.3%, 52.5%, and 49.2% in scenarios A.1, A.2, and A.3, respectively. However, surplus energy from VRES remains below 1% in all cases. In contrast, scenarios with ESSs (B.1–B.3) show that 63%, 70%, and 76% of the excess energy is effectively stored and reintegrated into the grid, underscoring the strategic role of storage in enhancing system flexibility and renewable utilization. Nonetheless, further research is needed to optimize storage capacity and deployment.

From an environmental standpoint, scenario A shows a notable reduction in climate change impacts compared to the Baseline (− 18.1% A.1; − 13.9% A.2; − 8.9% A.3), mainly due to increased renewable deployment. The inclusion of ESSs offers only marginal additional benefits (− 19.4% B.1; − 14.8% B.2; − 9.4% B.3), suggesting their primary contribution lies in operational stability rather than direct emission reduction.

Conversely, the indicator *resource use*, *minerals*, and *metals* shows a substantial increase in all 2030 scenarios (+ 92.9% A.1; + 84.3% A.2; + 74.6% A.3), largely due to the material demands of PV technologies. The addition of ESSs has a negligible effect on this trend (+ 93.0% B.1; + 84.4% B.2; + 74.8% B.3), highlighting potential trade-offs in resource consumption.

Finally, Single Score results confirm an overall environmental benefit in 2030 compared to 2020 (− 11.7% A.1; − 9.2% A.2; − 6.2% A.3). The presence of ESSs again yields only a modest improvement (− 12.7% B.1; − 9.9% B.2; − 6.6% B.3), indicating the need for continued optimization of storage systems to enhance their environmental performance.

This study highlights several key aspects coming from the adopted methodological approach, which needs further reflection.

Firstly, the integration of the IRENA FlexTool energy model with the LCA environmental model allows a clear estimation of the environmental impacts associated with the national electricity system, showing both the benefits and potential drawbacks. This coupling represents a significant contribution in terms of integrated modeling and can be readily extended to smaller geographical scales (e.g., regional or provincial), provided that more disaggregated and detailed input data are available. In fact, this work should not be viewed solely as a case study, but rather as a methodological proof of concept, demonstrating how the integration of energy system modeling with LCA can support more informed and holistic decision-making in the context of energy transitions.

Secondly, the application of LCA show both the positive effects and the critical issues associated with the environmental sustainability of the energy transition. As illustrated by the environmental indicators considered, the evolution of the power system towards low-carbon scenarios leads to a substantial reduction in climate-related impacts (e.g., CO_2-equivalent emissions), but it is also accompanied by an increased pressure on resource use, mainly due to the material intensity of renewable and storage technologies. Although the overall benefit is clearly demonstrated at the single score level, this prospective LCA study highlights the following issue. While the INECP, like other national energy strategies, is aligned with energy transition targets in terms of GHG emissions reduction, it also raises environmental concerns related to other aspects, such as the increased consumption of critical raw materials, which should be carefully considered in future planning efforts.

Another relevant finding of this study concerns the role of energy storage systems. While these technologies are essential for ensuring the operational flexibility of the power system, the results indicate that their contribution to the overall reduction of environmental impacts is relatively limited. This highlights the need for further investigation, particularly through the refinement of inventory data related to storage technologies and the development of more detailed modeling at sub-national scales.

Regarding the structure of the model and potential limitations arising from its generality and applicability, future studies will need to achieve even more accurate results, conducting multi-node electric grid modeling assessment. It will be essential to better understand the interactions among different regions in Italy. This will allow for a more comprehensive assessment of the contribution of storage systems in optimizing the entire national electric system. Exploring the dynamics and specific challenges of each geographical area could provide valuable insights for designing and implementing more effective and sustainable energy management strategies. Furthermore, enhancing the quality of the results could involve incorporating updated data from LCA databases or conducting a prospective analysis using predictive models within the LCA databases. Moreover, it should be noted that the methodology adopted did not include an economic analysis, which could be incorporated in future work to further enhance the holistic nature of the approach.

In conclusion, the potential role of a national grid-level ESS may be constrained by the limited smoothing effect it has on the demand and generation curve, especially when compared to small or single-user utilities. While large-scale energy storage systems are recognized as crucial for facilitating the transition to renewable energy, their impact may vary depending on factors such as geographical distribution and grid infrastructure. Consequently, despite grid-connected ESSs being recognized as crucial technology for energy transition, particularly in distributed behind-the-meter applications, their effectiveness in significantly reducing the environmental impact of the overall electric generation mix remains marginal. Additionally, challenges such as intermittency and mismatch between supply and demand patterns could limit the effectiveness of grid-connected ESSs in mitigating environmental impacts. However, ongoing advancements in energy storage technologies, coupled with supportive policies and grid modernization efforts, hold promise for enhancing the role of these systems in achieving a more sustainable electric generation mix.

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Data availability The authors make supplementary materials available, for further enquiries please contact them by email.

Declarations

Conflict of interest The authors declare no competing interests.

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