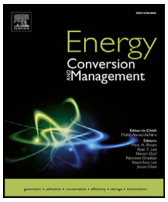
Energy Conversion and Management 286 (2023) 117019

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



Integration of battery and hydrogen energy storage systems with small-scale hydropower plants in off-grid local energy communities

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ARTICLE INFO

Keywords:
Battery energy storage system
Local energy community
Hydrogen storage system
Off-grid operation
Seasonal storage
Small-scale hydropower

ABSTRACT

The energy transition is pushing towards a considerable diffusion of local energy communities based on renewable energy systems and coupled with energy storage systems or energy vectors to provide independence from fossil fuels and limit carbon emissions. Indeed, the variable and intermittent nature of renewables make them inadequate to satisfy the end-users' electricity demand throughout the whole day; thus, the study of energy storage systems, considering their seasonal storage behaviour (e.g., energy-power coupling, self-discharge loss, and minimum state of charge) is fundamental to guarantee the proper energy coverage. This work aims at identifying the off-grid operation of a local energy community powered by a 220 kW small-scale hydropower plant in the center of Italy using either a battery energy storage system or a hydrogen one with the *Calliope* framework. Results show that, whereas the hydrogen storage system is composed of a 137 kW electrolyser, a 41 kW fuel cell, and a storage of 5247 kg_{H_2}, a battery system storage system would have a capacity of 280 MWh. Even though the battery storage has a better round-trip efficiency, its self-discharge loss and minimum state of charge limitation involve a discharging phase with a steeper slope, thus requiring considerable economic investments because of the high energy-to-power ratio.

1. Introduction

The worldwide green energy transition is currently pushing towards a considerable change of the power generation sector. A new concept of both energy production and use is being applied, shifting the centralised electrical energy production to the distributed one with an active approach of the end-users that become "prosumers" when dealing with Local Energy Communities (LECs).

Renewable Energy Systems (RESs) are crucial for achieving this goal; indeed, it is expected that almost 90% of the global electricity generation will be produced by RESs within 2050, where both solar and wind energy will account for almost 70% [1]. Nevertheless, the future increase of RESs penetration is mainly connected to the national grid that will inevitably lead to stricter network regulations from both technical (e.g., grid stability and controllable & dispatchable plants) and economic (e.g., grid parity and competitive bidding) points of view [2]. Up to now, only Iceland and Paraguay produce 100% of the electricity from renewables, while other countries like Costa Rica, Ethiopia, Kenya, Namibia, Norway, Tajikistan, and Uruguay are currently generating more than 90% of electricity from renewables [3]. Italy is a high energy intensive and industrialised country where only 20% of energy is produced by renewables, while 77.3% comes from the use of oil or natural gas that is still an important value that leads to a relevant carbon footprint. In addition, almost 6% of the produced energy, when injected into the grid, is subjected to network losses that increase considerably the inefficiency of the current electrical infrastructure [4].

Energy Storage Systems (ESSs) that decouple the energy generation from its final use are urgently needed to boost the deployment of RESs [5], improve the management of the energy generation systems, and face further challenges in the balance of the electric grid [6]. According to the technical characteristics (e.g., energy capacity, charging/discharging dynamics, Depth Of Discharge (DOD) range, power/energy ratio, and self-discharge rate), each ESS can be suited for a specific application [7]. Wang et al. [8] carried out a complete overview of different ESSs and they evaluated their performance in

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https://doi.org/10.1016/j.enconman.2023.117019

mitigating the fluctuation and uncertainty of energy production from renewables. They observed that the capability of an energy storage technology to handle the unpredictability of such sources can vary due to different control methods, which are the key factors for exploiting renewables optimally.

Nomenclature

Acronyms

BECS	Building Energy Codes Program
BEP	Best Efficiency Point
BESS	Battery Energy Storage System
DOD	Depth Of Discharge
ESS	Energy Storage System
GME	Gestore Mercati Elettrici
LCA	Life Cycle Assessment
LEC	Local Energy Community
LHV	Lower Heating Value
MILP	Mixed Integer Linear Programming
MVF	Minimum Vital Flux
O&M	Operation & Maintenance
P2P	Power-to-Power
PEM	Proton Exchange Membrane
PUN	Prezzo Unico Nazionale/Single National Price
RES	Renewable Energy System
SOC	State Of Charge

Parameters

δ	Minimum storage SOC [0–1]
ϵ	Storage self-discharge ratio [0–1]
η	Conversion efficiency, [0–1]
C	Costs [€]
c	Unitary costs, *either* [€/kW] *or* [€/kWh]
$CAPEX$	Technology investment cost, *either* [€/kW] *or* [€/kWh]
d_r	Depreciation rate [-]
i	Interest rate [0–1]
lt	Life time [years]
$O\&M$	O&M technology cost [0–1]

Subscripts

$cons$	Consumed
ESS	Energy storage system
fix	Fixed
h	hth timestep; $h \in H$
j	jth technology; $j \in J$
$prod$	Produced
$stored$	Stored
tot	Total
var	Variable
y	Year

Variables

E_{cons}	Energy consumed in a system $[-S_i - 0]$
E_{prod}	Energy produced in a system $[0 - S_i]$
S	Technology size, *either* [kW] *or* [kWh]
LCOS	Levelised Cost Of Storage [€/kWh]

So far, both economic and environmental issues, as well as challenges and limitations, have been discussed in the scientific literature: characteristics, advantages, limitations, costs, and environmental considerations have been compared to provide useful outcomes for different stakeholders in the energy sector. ESSs are crucial actors to enable electricity self-consumption in small-scale renewable energy systems, thus fostering the efficient use of local energy resources and reducing the electricity withdrawal from the national grids [9]. The advantages of ESSs are twofold: firstly, the end-users do not overload the national grid, thus contributing positively to its safety and stability [10]; secondly, the on-site RESs' management optimisation decreases the energy losses as well as the greenhouse gases emissions. Klumpp [11] studied different ESSs technologies from both energy and economic points of view, focusing mainly on mechanical (e.g., pumped hydro and compressed air energy storage) and chemical ones (e.g., hydrogen storage). The levelised cost of electricity has been taken into account in different dispatch scenarios like short-, medium-, and long-term storage; furthermore, other indicators like efficiencies, capital expenditure & operational expenditure, and technical service lives have been considered. Results showed that pumped hydro is currently the most cost-efficient short- and medium-term storage technology, which is followed by compressed air energy storage. Hydrogen might be more competitive in the near future, representing a possible solution for long-term energy storage. However, it is worth noting that, among the mechanical ESSs technologies, pumped hydro is not always feasible since it is strictly dependent on the morphological characteristics of the site, thus not being applicable everywhere.

Among ESSs, Battery Electric Storage System (BESS) is one of the most known and commonly used. BESSs are highly modular and suited for decentralised applications at different scales since they are characterised by a high round-trip efficiency and fast charging/discharging dynamics [12]. However, BESSs present relevant self-discharge phenomena due to the crossover reactions and material degradation that limit their long-term storage capabilities [13]; indeed, they can present a 5% loss of stored energy in a month [14].

On the other hand, as previously said, long-term chemical-based ESSs (e.g., hydrogen storage) are promising solutions due to the higher energy density and stability over time compared to BESSs [15]. Electricity is converted into chemical energy in the form of hydrogen molecules that can be either re-electrified with fuel cells or dispatched as a renewable feedstock for other end-use purposes [16]. Elberry et al. [17] investigated the use of large-scale hydrogen storage technology in Finland over longer time periods. This solution is highly suitable for RESs due to their seasonality, especially in summer and winter when both electricity production and consumption are sensibly different. Furthermore, the hydrogen storage technology led to a CO_2 reduction of 69% due to the lower use of fossil fuel-based power plants. At the same time, although the energy loss in the round-trip conversion is considerable, the hydrogen storage solution is suitable for long charging/discharging periods due to the high energy density per unit of mass and long-term stability in its stored form [18]. Since the hydrogen storage solution is based on open conversion systems (e.g., electrolyser and fuel cell), the stored energy volume depends only on the storage capacity, and it does not affect the power rating of the conversion systems; in this way, substantial increases in the investment costs can be avoided [19].

Several scientists have investigated hydrogen-hydropower coupling. Indeed, Bødal et al. [20] analysed the hydrogen production from wind power and hydropower in Norway. They formulated and implemented a stochastic rolling horizon model to consider the wind power stochasticity when operating flexible hydrogen loads. The model has been validated with a wind power scenario and results showed that the stochastic model gave a better management strategy than the deterministic one, thus being a promising solution for further cost reductions by improving the forecasting capability. Furthermore, this study revealed that green hydrogen storage is important to avoid rationing in certain situations and increase the power flow as well. Furthermore, Liu et al. [21] worked on a case study located in China, coupling hydropower and hydrogen storage systems. Hydropower resources are strictly dependent on the morphological characteristics of the country, especially those that are geographically wide. The difficulty of using instantaneously the electricity produced through hydropower can lead to a large amount of unused hydraulic potential, thus contributing to both energy and economic losses. In response to this, ESSs technologies like hydrogen storage can provide a possible solution for the non-optimal exploitation of the water resource, providing also power for grid-connected generation during the dispatching operation of the power grid, as well as energy islands that are self-sufficient from an energy point of view. In particular, they analysed different electrolysers technologies, hydrogen storage technologies, and fuel cell technologies, showing their current pros and cons as well as enlightening the importance to build new power systems to reach the zero-net carbon emission target.

However, the abovementioned works [20,21] have not compared the use of BESS with the hydrogen storage systems, which is important for assessing the profitability of those ESSs technologies according to both availability and localisation of some renewable sources. Generally, BESSs and hydrogen storage systems are being used for short- and long-term periods, respectively; thus, their comparison in terms of both the design and the usage is crucial for properly assessing their optimal operation. For sure, the characteristics of the renewable source affect considerably the choice of the two previous technologies, providing an advantage of one of them over the other [22]. Indeed, BESSs and hydrogen storage systems have been already defined by other researchers as mutual alternatives to be embedded in the energy systems [23]. However, both ESSs have been identified as attractive solutions in different combinations to enhance the reliability and resiliency of national grids and energy systems. Chadly et al. [24] focused on a commercial building in Los Angeles, California (USA) as a case study assessing the feasibility of the two different energy storage technologies; in particular, BESSs were more convenient than hydrogen storage systems from an economic point of view. Belmonte et al. [25] analysed an off-grid renewable energy system: the hydrogen storage solution was more expensive than the BESS; however, the Life Cycle Assessment (LCA) analysis of the hydrogen storage system showed a lower environmental impact. The same results have been also obtained by [26], even though they referred to a different application.

To the authors' knowledge, a detailed comparison between BESSs and the hydrogen storages, coupled with a renewable production having high seasonality variations to provide off-grid operations of a LEC, has not been investigated in detail so far. Indeed, two different energy storage scenarios focusing on seasonal storage behaviour are mandatory to properly assess the ESSs' design: this analysis is of big interest due to the high variability of most of the renewables throughout the year.

This work aims at investigating different ESSs, namely the BESS and the hydrogen storage system, coupled with an existent 220 kW small-scale hydropower plant for fulfilling the electricity demand of a LEC completely. Both technologies are analysed over a year to achieve an off-grid, decarbonised LEC. All the scenarios are analysed with a model-based approach by implementing the energy modelling framework *Calliope*, which is based on a Mixed Integer Linear Programming (MILP) algorithm, to minimise the user-defined objective.

By assessing the seasonal application of this ESSs integration to provide a fully grid-independent operated LEC, the main contributions of this work to the scientific literature are the following:

- provide an investigation on the loss of BESSs' stored energy when dealing with long-term storage;
- assess the hydrogen storage benefits in LECs since it is not subjected to stored energy loss over time;
- investigate energy-power coupling issues due to the ESSs' integration;
- compare the Levelised Cost Of Storage (LCOS) of both ESSs technologies in seasonal storage applications.

The paper is structured as follows: Section 2 provides information about the adopted methodology, which is divided into two stages that are described in detail. In addition to the case study's characteristics, the main three steps applied to each stage for carrying out the analysis are (i) the input data, (ii) optimisation problem formulation, and (iii) evaluation criteria. Section 3 reports the outcomes of both stages; precisely, this section is divided into two subsections where the grid-connected LEC is studied, and another one where two different scenarios of off-grid operations of the LEC are analysed. Finally, Section 4 reports the conclusions of the work.

2. Materials & methods

In this section, the method used to compare BESS and hydrogen storage systems coupled with a small-scale hydropower plant for the off-grid operation of a LEC is described in detail. Based on historical data of (i) the small-scale hydropower plant's power production, (ii) Italian energy price, and (iii) the LEC's electricity demand, all of them with an hourly resolution, a two-stage study is performed with the *Calliope* framework.

The description of both stages, as well as the connection between the involved energy systems, are reported; then, the case study under investigation is described by reporting all operational data required for the analysis. Finally, a description of the adopted modelling framework *Calliope* is reported.

2.1. Description of the two-stage analysis

As previously mentioned, the analysis is divided into two distinct stages, namely baseline and off-grid operation one. Their main characteristics are described as follows:

1. The baseline stage (Fig. 1) is the case where no energy storage is present. In this case, the overall energy demand is mainly provided by the national grid and, when available, from the small-scale hydropower plant. The use of the hydropower electricity over the one withdrawn from the national grid is driven by the market cost, which is different in the two cases. When the small-scale hydropower plant's production is higher than the LEC's energy demand, the energy surplus is injected into the grid. Such a stage represents the benchmark scenario that allows having a reference case of the current situation (on-grid operation) and a base for carrying out the analysis with the implementation of ESSs.
2. Off-grid operation stage assesses the grid independence of the LEC, and it is further divided into two scenarios:
    - the BESS scenario (Fig. 2) assesses the off-grid operation of the LEC with a battery, where both capacity and energy management are considered. Technological barriers, such as self-discharge losses, are also included;
    - the hydrogen scenario (Fig. 3) assesses the Power-to-Power (P2P) route for the off-grid operation of the LEC. This stage is devoted to the design of the electrolyser, the hydrogen storage, and the fuel cell, stressing the energy (hydrogen storage) - power(electrolyser/fuel cell) decoupling.

In the off-grid operation, a seasonal energy storage strategy has to be considered to provide the off-grid operation of the LEC because of the fluctuation of the small-scale hydropower production in some months of the year. Precisely, this strategy consists in storing the energy surplus produced by a RES system into an ESS for an extended period of time and using it afterward, when the RES system is not operating, to fulfil the energy demand of the LEC completely. Thus, the national grid has been excluded in this stage; indeed, the main three elements

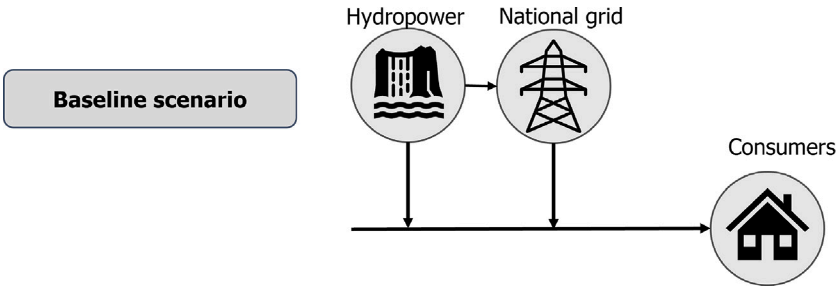


Fig. 1. Baseline scenario (on-grid operation of consumers).

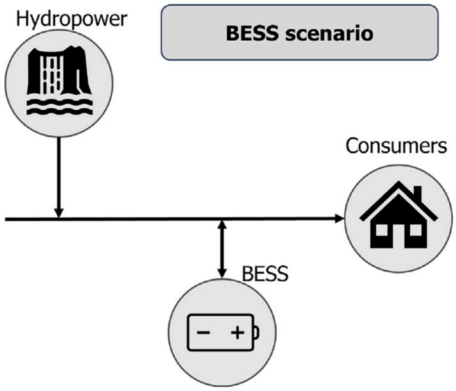


Fig. 2. BESS scenario (off-grid operation of consumers).

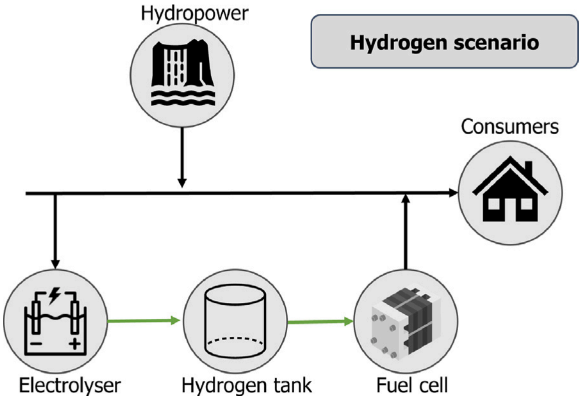


Fig. 3. Hydrogen system scenario (off-grid operation of consumers).

involved in the analysis are (i) the small-scale hydropower plant, (ii) the end-users' demand, and (iii) the ESS.

As reported in Fig. 2, the BESS is modelled as a single component. On the other hand, even though the hydrogen storage system can be considered a single energy storage solution, it has been divided into two conversion systems (e.g., electrolyser and fuel cell) plus one storage (e.g., hydrogen tank) to evaluate the power and energy decoupling nature of this solution. It is worth noting that both the BESS and the hydrogen storage system have been analysed separately. Only the re-electrification through a fuel cell is studied in the hydrogen system scenario to compare two P2P storage routes; in this way, it is possible to perform a comparative analysis of the two ESSs by addressing their technical and economic differences.

2.2. *The single national price of the Italian energy market*

In the case of the on-grid operation of the LEC, the electricity cost takes the name of the "Single National Price" (PUN), which is the wholesale reference price of the electricity that is purchased from the electric market. The PUN represents the national weighted average of the zonal sales prices of the hourly electricity day, and it considers both quantities and prices formed in the different areas of Italy and at different day times. The historical values of the PUN (hourly resolution) are publicly accessible in the National Energy Market Operator named "Gestore dei Mercati Energetici" (GME) database [27]. In this work, the historical data of the PUN regarding year 2019 have been adopted, thus ensuring the time-horizon alignment with the hydropower plant production data.

In 2019, as reported by Fig. 4, the PUN values varied between 0.01–0.12 €/kWh and its daily trend is recurrent throughout the year. As it is highlighted by the same figure, its value has skyrocketed starting from 2021 due to the energy crisis. Indeed, from 0.05 €/kWh of January 2019, it has achieved a value of 0.4 €/kWh in December 2022, thus further enhancing the economical importance of operating in off-grid mode. The time period between 3–6 am is characterised by the lowest PUN value of that day, while it increases during the day at 10–12 am until the maximum daily value is achieved at 6 pm.

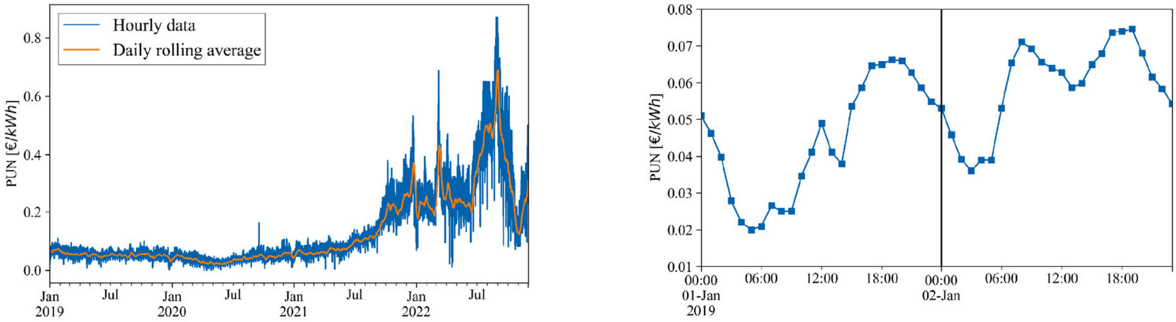
2.3. *Case study*

The case study under investigation is described in this subsection where both the nature of the data and their origins are reported.

2.3.1. *Small-scale hydropower plant*

The case study consists of a 220 kW small-scale hydropower plant (e.g., run-of-the-river) in the Center of Italy. It is constituted by a Kaplan turbine with movable runner blades to adjust their operating point according to the available flow rates. The main characteristics and performance curves of the Kaplan turbine are shown in Table 1 and Fig. 5, respectively. In particular, the Best Efficiency Point (BEP) is obtained at 417 rpm with a flow rate of 3.04 m^3/s and a head of 4.05 m with an overall efficiency of 90%. An inverter is also connected to the electric generator of the hydraulic turbine to provide more flexibility to the machine operation by shifting the operating point while changing the rotational speed: indeed, this procedure allows the hydraulic turbine to operate in a wider range of flow rates keeping high hydraulic efficiency.

Hydropower generation implies variable power production throughout the year since it depends on the occurrences of rainfalls, and thus on the flow rate of the water resource. Fig. 5 shows the measured data of the power output of the hydraulic turbine in 2019. The seasons characterised by a lack of hydropower production are usually the spring and the summer when the water shortages do not allow the hydropower plants to operate at their rated operating conditions. The Minimum Vital Flux (MVF) defined by the legislation of each country, which must be guaranteed to preserve both the local flora and fauna [28], affects the variability of the hydropower plants' production. The average power output recorded in 2019 was equal to 70.07 kW considering the shutdown of the small-scale hydro-power plant in two periods of the year (e.g., March–April and July–November), as previously mentioned, where the second extended shutdown lasts more than 140 days.



(a) Historical trend of the PUN

(b) Daily trend of the PUN (e.g., 1st and 2nd of January 2019)

Fig. 4. Single National Price (PUN)

Table 1
Main characteristics of the Kaplan turbine.

Parameter	Value	Unit of measure
Diameter	0.9	m
Rotational speed	417	rpm
# of blades	5	–
Head	4.05	m

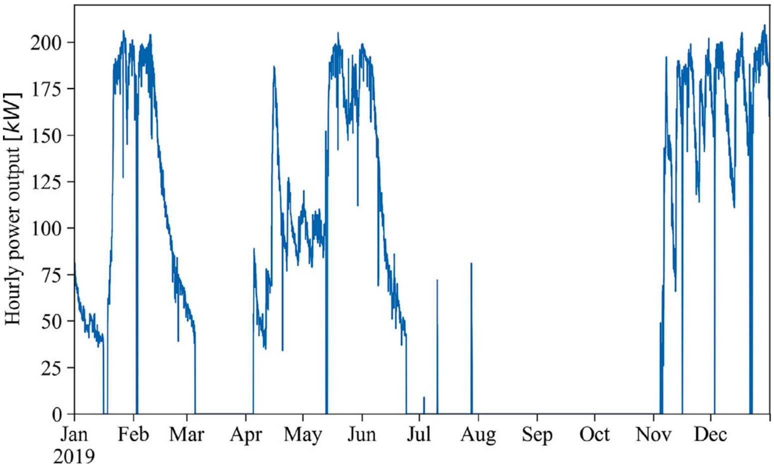


Fig. 5. Trend of hourly power output of the small-scale hydropower plant in 2019.

2.3.2. *Energy demand of the local energy community*

The electricity demand of the end-users is required to obtain the design requirements of the ESSs. Due to the lack of data related to the end-users close to the small-scale hydropower plant, the energy demand has been obtained using the “mid-rise apartment” dataset of the Building Energy Codes Program (BECS), which is a database widely used in the scientific literature by assuming the characteristics of the loads [29]. The “mid-rise apartment” from BECS is a non-industrial, multi-use building (both residential and offices) divided into 4 floors with 32 small apartments that cover an overall area of nearly 3,400 m^2. The electric load is reconstructed through (i) the occupancy of the end-users and the electrical activities during the day (e.g., appliances and lighting), (ii) the rated surface, and (iii) the specific electric power consumption by lighting and appliances as shown in Fig. 6. It is possible to modify the data of the 32 small apartments of the single building with 32 stand-alone houses and offices, thus constituting a small-scale LEC to analyse a more common urbanistic environment in Italy. Furthermore, this modification does not affect the overall electricity consumption and the model output since the total energy demand is taken as a whole as input of the model.

The yearly electric load is simulated with a recurrent daily trend (hourly resolution). During the day, the trend follows the occupancy and the people’s behaviour at work/home. Finally, the energy is equal to 614 kWh/day, thus resulting in a maximum stored energy requirement of 85 MWh for the maximum hydropower plant shutdown (about 140 days as described previously in 2.3.1).

2.4. *Calliope modelling framework and design optimisation problem*

All the three stages previously described are investigated through a system-level simulation using the energy modelling framework *Calliope* which is an open-source, multi-energy system modelling, and optimisation framework that analyses the energy systems with user-defined spatial and temporal resolutions. Furthermore, it also allows modelling energy systems at different levels through a scale-agnostic mathematical formulation based on the power nodes modelling framework proposed by Heussen et al. [30]. *Calliope* is based on a bottom-up approach; indeed, every single energy system (j) is modelled with its own characteristics and constraints based on the type of technology (e.g., supply, conversion, storage, demand, and transmission). The most simple energy system is characterised by time-dependent consumed ($E_{cons_{(j,h)}}$) and produced energy ($E_{prod_{(j,h)}}$) passing through the efficiency of the system (η_j) as illustrated in Fig. 7.

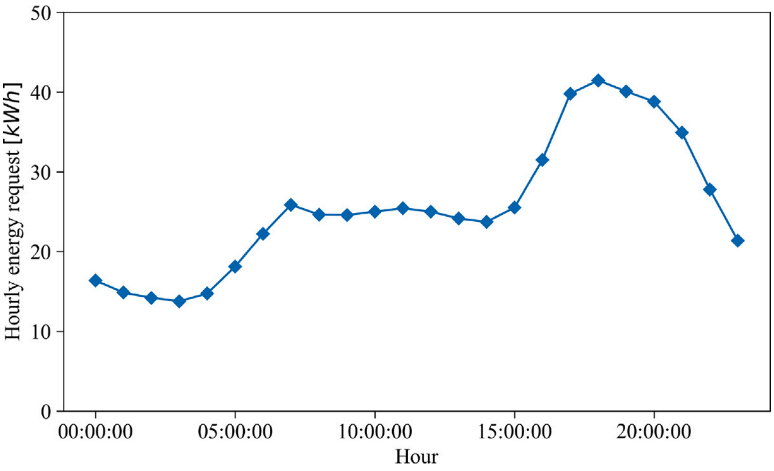


Fig. 6. Daily electrical load of the LEC [29].

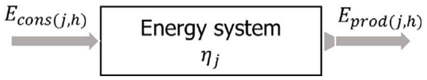


Fig. 7. *Calliope* modelling approach.

For all the three stages of the study, the optimisation problem aims to find the best economic system design to provide the energy request during the entire planning horizon. Such a problem can be described by the following equations where the objective is:

$$min\,:\,z=\sum_{j}^{J} C_j \tag{1}$$

where C_j are the costs of each energy system involved in the study. Additionally, the problem is subjected to the following technical constraints:

$$\sum_{j,h}^{J,H} E_{prod_{(j,h)}} = \sum_{j,h}^{J,H} E_{cons_{(j,h)}} \tag{2}$$

$$E_{prod_{(j,h)}} + E_{cons_{(j,h)}} \cdot \eta_j = 0 \tag{3}$$

$$E_{prod_{(j,h)}} \leq S_j \quad \forall h \in H \tag{4}$$

$$E_{stored_{(j,h)}} = E_{stored_{(j,h-1)}} \cdot (1-\epsilon_j) - E_{cons_{(j,h)}} \cdot \eta_j - \frac{E_{prod_{(j,h)}}}{\eta_i} \tag{5}$$

$$S_j \cdot \delta_j \leq E_{stored_{(j,h)}} \leq S_j \quad \forall h \in H \tag{6}$$

$$E_{prod} \geq 0; E_{cons} \leq 0 \tag{7}$$

While the overall systems energy balance is described in Eq. (2), Eq. (3) is the energy conversion process and Eq. (4) sets the technology size constraint (S_j). Finally, storage technical characteristics, including the self-discharge behaviour (ϵ), is present in the hourly balance in Eq. (5) as well as the minimum State Of Charge (SOC/δ_j) reported in Eq. (6).

The national grid is modelled as an unlimited supply, meaning that it is an energy system that has only E_{prod}, which is variable and associated with both economic (PUN, time-dependent) and environmental costs, where the latter is set equal to 281.4 gCO_2/kWh as reported by the Italian energy and climate regulatory agency [31]. The small-scale hydropower plant, instead, is an energy system with already known E_{prod} over the entire planning horizon since its historical production data is known. Finally, the energy demand is modelled as an energy system with only E_{cons}, which is time-dependent but known as input data.

As an economic evaluation, *Calliope* allows defining different costs that are divided into fixed (e.g., investment costs related to the capacity of the technology and the Operation and Maintenance (O&M) ones that are expressed as a fraction of the investment cost) and variable. Furthermore, the depreciation rate is adopted to compare different types of technologies:

$$d_r = \frac{i \cdot (i+1)^{lt}}{(i+1)^{lt} - 1} \tag{8}$$

where d_r is the depreciation rate, lt the lifetime of the technology expressed in years, and i is the interest rate. The depreciation rate allows comparing all the technologies into an equivalent year considering the different lifespans and interest rates as well. Hence, the overall cost for a single technology is the sum of all of the costs previously mentioned:

$$C_j = C_{fix} + C_{var} = S_j \cdot CAPEX \cdot d_r(1 + O\&M) + c_{var} \cdot E_{prod_{(j)}} \tag{9}$$

that is divided into fixed costs (C_{fix}) and variable ones (C_{var}). While the fixed part is strictly dependent on the technology size S, which is the design variable of the optimisation model, $CAPEX$ represents the investment cost of the technology expressed either in €/kW or €/kWh, and O&M is the operation and maintenance costs of the technology expressed as a ratio of the investment cost. Regarding the variable part, it depends on the operational strategy; indeed, it is based on the energy produced and the cost per kWh of produced energy (c_{var}).

Based on the case study's characteristics, only supply technology (e.g., national grid and small-scale hydropower plant), conversion technology (e.g., electrolyser and fuel cell), storage (either Li-ion battery or hydrogen tank), and energy demands are included in the analysis. Still, *Calliope* offers more advanced and complex modelling in terms of both technology types and constraints; however, since this is not the focus of the study, further details can be found in [32]. The techno-economic parameters of the BESS and the hydrogen storage system (e.g., Proton-Exchange Membrane (PEM) electrolyser, PEM fuel cell, and compressed hydrogen tank) are listed in Tables 2 and 3, which have been taken as a reference for the inputs of the *Calliope* model [33]. It is worth noting that Proton Exchange Membrane (PEM) electrolyser and fuel cell have been chosen due to their high technology readiness level and availability in the market. Furthermore, the good performance at a low current density makes them suitable for managing transient loads as in the case of the hydropower plant under investigation. These parameters are not included for the small-scale hydropower plant yet since it is an already existent installation with previously monitored data. Regarding the BESS, the technical parameters such as round-trip efficiency and

Table 2
Main characteristics of the ESSs.

	Value	Unit	Ref.
BESS			
Round-trip efficiency	91	%	[33]
Self-discharge ratio	0.007	%/hour	[34]
Minimum SOC	20	%	[33]
Hydrogen			
Electrolyser efficiency	71	%	[33]
Fuel cell efficiency	50	%	[33]

Table 3
Cost parameters of the study.

Costs	Value	Unit of measure	Ref.
BESS investment cost	285	€/kWh	[33] [35]
BESS O&M annual costs	2.2	%	[33] [35]
BESS lifetime	12	years	[33] [35]
Electrolyser investment cost	1,295	€/kW	[33] [35]
Electrolyser O&M annual cost	3.5	%	[33] [35]
Electrolyser lifetime	15	years	[33] [35]
Hydrogen storage tank cost	30	€/kWh	[12] [35]
Hydrogen storage tank O&M cost	2.3	%	[12] [35]
Hydrogen storage tank lifetime	30	years	[12] [35]
Fuel cell investment cost	1,684	€/kW	[33] [35]
Fuel cell O&M annual cost	2	%	[33] [35]
Fuel cell lifetime	14	years	[33] [35]
Interest rate (all systems)	2	%	[33] [35]

minimum SOC have been taken from the scientific literature [33]. The self-discharge rate, which is defined as the hourly loss of the stored energy over time and expressed as a percentage of the previously stored energy, was adjusted to have a calendar aging (without BESS operation) of 5% in a month, which is aligned with the data available in the scientific literature [34]. On the other hand, the conversion efficiencies of the two systems (e.g., PEM electrolyser and fuel cell) are considered separately in the hydrogen storage system. It is worth noting that the minimum SOC and the self-discharge rate of the compressed hydrogen tank are not applicable. Indeed, it has been assumed that the charging and discharging phases occur via a mass transfer of the hydrogen with no losses.

2.5. Evaluation indicators

Both off-grid operating stages' designs are assessed to further compared them both technically and economically. Additionally, the LCOS has been calculated to evaluate and compare the competitiveness of the two ESSs to store energy over a fixed time period. The LCOS analysis is performed daily and for a period of 140 days. In particular, the analysis of the LCOSs trend with increasing storage periods from a day up to 180 days (e.g., stored energy volumes) allows evaluating the storage duration limit that indicates the competitiveness of each ESS. The rated BESS capacity per scenario is obtained considering the self-discharge calculated on an operational basis. The LCOS analysis is carried out with the same economic parameters reported in Table 3, thus evaluating the number of cycles that the ESS can sustain with an overall time horizon of 20 years. The LCOS is calculated as follows:

$$LCOS = \frac{C_{ESS,y}}{E_{stored,y}} \tag{10}$$

where $C_{ESS,y}$ is the annualised cost of the selected scenario obtained with the economic parameters reported in Table 3, and $E_{stored,y}$ is the total energy volume that could be annually stored in the ESS. The latter considers the number of charging/discharging cycles according to the storage period, where the charging duration is assumed to be equal to the discharging one.

Table 4
BESS scenario results.

BESS scenario	Value	Unit of measure
BESS capacity	280	MWh
BESS power	193	kW
BESS energy-to-power ratio	1,451	–
Min charge	56	MWh
Min SOC	20	%
Annualised BESS cost	3.38	M€/year
Overall cost	5.61	M€/year
LCOS	50,271	€/MWh

Table 5
Hydrogen scenario results.

Hydrogen scenario	Value	Unit
Electrolyser capacity	137	kW
Hydrogen storage tank capacity	5,247	kg_{H2}
Hydrogen storage tank capacity	175	MWh
Fuel cell capacity	42	kW
Annualised electrolyser cost	14.2	k€/year
Annualised hydrogen storage tank cost	290.5	k€/year
Annualised fuel cell cost	5.9	k€/year
Overall annualised cost	0.31	M€/year
LCOS	2,958	€/MWh

3. Results and comments

In this section, the results of analysed scenarios are reported and discussed. Firstly, the baseline scenario's results give an overview of the grid-connected stage, which is then followed by the off-grid operation mode, highlighting the implications of such a decision.

3.1. Baseline scenario

As previously mentioned, the first stage refers to the standard operation mode where no energy storage is used. As it can be noticed in Fig. 8, the LEC cannot operate in off-grid mode using only the electricity produced by the small-scale hydropower plant due to its discontinuous energy production throughout the year.

Fig. 9 shows that, in a single year, about 104 MWh of electricity from the grid (46%) and about 122 MWh of electricity from the small-scale hydropower plant (54%) is required by the LEC to fulfil its overall energy demand. In this case, there are both economic and environmental costs due to the dependence of the LEC on the national grid.

3.2. Off-grid operation mode

The cost-optimal model determines the lowest values of the design parameters of the BESS and the hydrogen storage system to supply the energy demand of the LEC in the whole period of the small-scale hydropower plant shutdown by exploiting the surplus of the stored energy. Results for the design parameters of both the ESSs to meet the long-term storage requirements, including also the characteristics of the technologies, are reported in Tables 4 and 5 as follows:

- BESS storage: 280 MWh (capacity) and 193 kW (maximum power rating during the charging phase);
- Hydrogen storage: 137 kW electrolyser, 5247 kg of hydrogen tank capacity (175 MWh, based on the Lower Heating Value (LHV) of hydrogen), and kW fuel cell.

While the BESS capacity sizing is mainly driven by the energy rating (e.g., a larger stored energy volume implies a larger capacity), the sizing of the hydrogen system follows the power rating for the conversion systems and the energy rating for the hydrogen tank. Following the power production profile of the small-scale hydropower plant, the

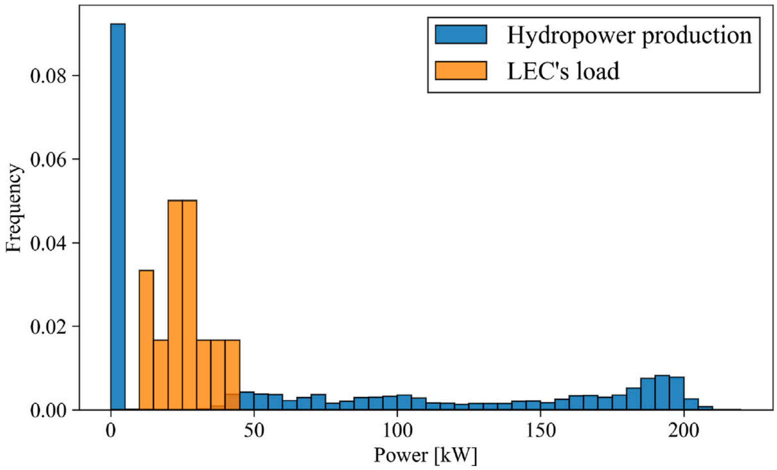
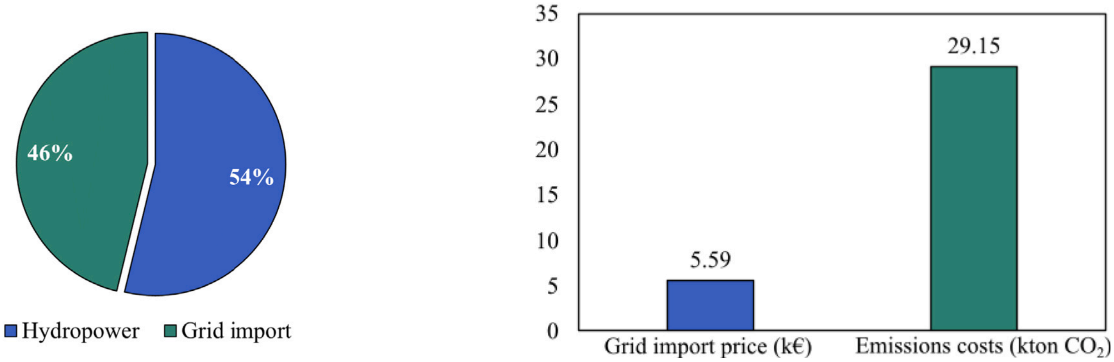


Fig. 8. Production and load frequencies (sorted by power).



(a) Load share

(b) Baseline costs

Fig. 9. Baseline scenario results.

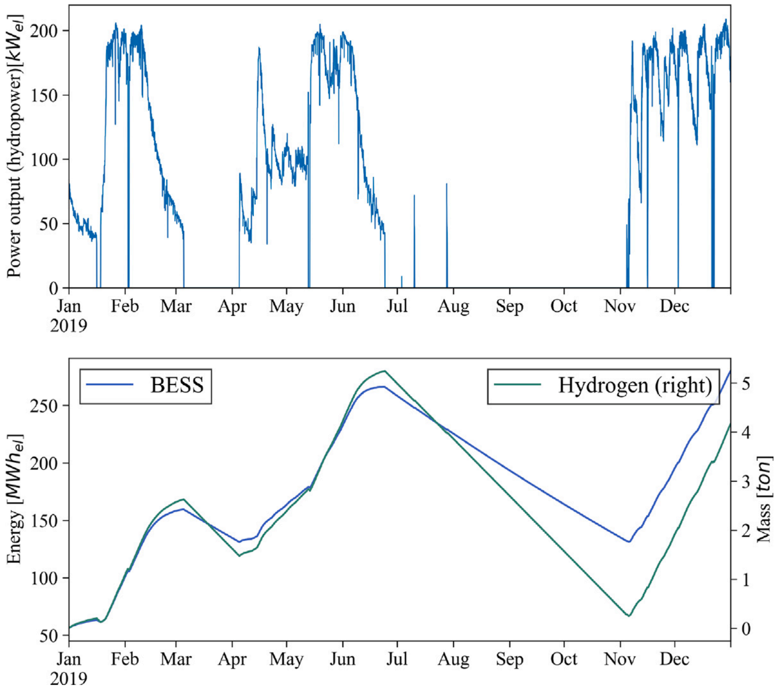


Fig. 10. Small-scale hydropower production (top) and the charging/discharging phases of the two ESS solutions (bottom).

operational SOC of the ESSs (Fig. 10) reaches its peak at the end of the producibility before using the stored energy capacity to cover the lack of the small-scale hydropower plant operation. Due to the minimum SOC constraint (e.g., 20% of the capacity), high efficiency (91%),

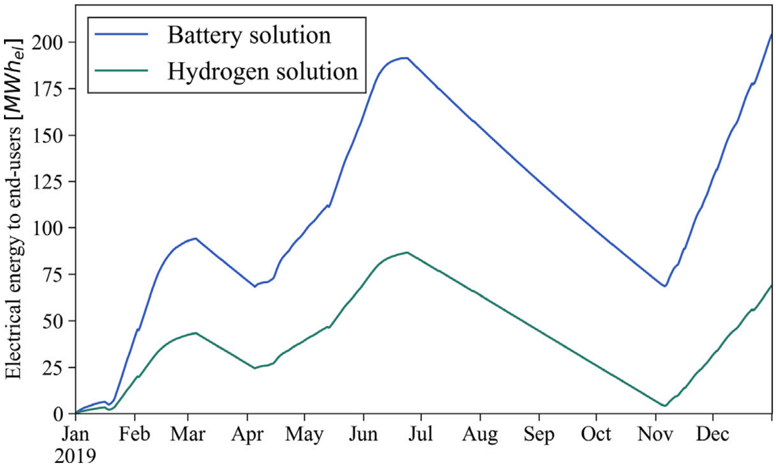


Fig. 11. Available electrical energy to end-users from the two ESS solutions.

and modest self-discharge, the BESS capacity is discharged during the lack of the small-scale hydropower production (July–November), but it is not completely depleted. Furthermore, due to the higher charge efficiency, its energy capacity remains higher than the one of the hydrogen tank during the subsequent start-up of the small-scale hydropower plant after the long period where it did not operate (e.g., November–December).

It is worth noting that a cyclic SOC (e.g., the SOC at the end of the evaluation time) for this case study cannot be achieved due to the characteristics of the plant since there is a gap between the yearly hydropower production and consumption; therefore, there is an abundant excess of hydrogen (i.e. 4155 $\mathrm{kg_{H_2}}$) stored in the hydrogen tank or electrical energy stored in the BESS (i.e. 280 MWh) at the end of the year.

The electrical energy that can be delivered from both ESSs to the LEC is reported in Fig. 11. It is possible to spot that, with the inclusion of the battery self-discharge loss, the available electrical energy has a steeper slope and decreases much faster than the hydrogen storage system. For larger stored volumes, the possibility of decoupling the power and energy rating allows sustaining moderate sizes of the conversion systems (e.g., electrolyser and fuel cell) that are the most expensive components. For this reason, the total cost and LCOS of the hydrogen solution (0.31 M€/year; 3 k€/MWh) is significantly more competitive with respect to the BESS (5.61 M€/year; 50 k€/MWh) as an effect of the high energy-to-power ratio, thus leading to an uneconomical result in terms of BESS investment cost.

By analysing the LCOS trend reported in Fig. 12, it can be observed that, with increasing storage periods, the hydrogen storage system is more competitive when dealing with periods greater than 30 h (e.g., between 1–2 days) and energy volumes greater than nearly 1 MWh. The intersection of the LCOS curves related to the two ESSs occurs at around 400 €/MWh. For energy volumes higher than 1 MWh, the additional cost for a larger BESS exceeds the CAPEX of the hydrogen conversion system, while the hydrogen storage tank only marginally contributes to the LCOS. For storage periods beyond 1,000 h (about 40 days), the LCOS of the BESS storage (about 10 k€/MWh) is one order of magnitude higher than the LCOS of the hydrogen storage (about 1 k€/MWh). The LCOS trends are coherent with what has been previously discussed regarding the sizing of the hydrogen storage system and the scientific literature as reported in [36].

4. Conclusions

In this work, the integration of different ESSs coupled with a 220-kW small-scale hydropower plant (e.g., run-of-the-river) is investigated to provide an off-grid operated 48 kW LEC. Specifically, a BESS and a hydrogen storage system are used as P2P route and their energy and economic performance are compared. In particular, the study consisted in three stages, where firstly the baseline scenario is analysed to be then followed by other two stages related to the off-grid operation of the LEC with two different ESSs (e.g., BESS and hydrogen storage system).

Despite the difference in the rated power between the small-scale hydropower plant and LEC's energy demand, the former satisfies 54% of the LEC's energy demand, while the rest is covered by the electricity withdrawn from the national grid with an expense for power purchasing of 5.59 k€ and a carbon footprint of 29.15 $\mathrm{kton_{CO_2}}$ per year. However, such expenses can be avoided with a LEC operating completely off-grid.

Off-grid operation requires the prerequisite of seasonal storage integration, meaning storing the energy surplus produced by the small-scale hydropower plant into the ESS for an extended period of time (months). Afterwards, this stored energy is used to fulfil the LEC's energy demand completely when the small-scale hydropower plant is not running. With the focus on achieving a fully electrically sustainable LEC (e,g., complete off-grid operation), the ESSs technologies have been considered separately.

While the hydrogen storage can meet the storage requirements through a 137 kW of electrolyser, 42 kW of the fuel cell, and a 5247 kg capacity hydrogen tank (173 MWh), the BESS must have 280 MWh of energy capacity. The inclusion of the BESS self-discharge loss behaviour makes its discharging slope much steeper than the hydrogen discharging one. Furthermore, it has a higher round-trip efficiency but, since it is an energy-power coupled into a single energy system, it is not anymore economically convenient compared to hydrogen when a high unbalance among such parameters (e.g., extremely high Energy-to-Power ratio) is present.

Indeed, by analysing the LCOS trend, it can be observed that, with increasing storage times, hydrogen is more competitive when dealing with periods greater than 30 h (e.g., between 1–2 days) and energy volumes greater than nearly 1 MWh. For energy volumes higher than 1 MWh, the additional cost for a larger BESS exceeds the CAPEX of the hydrogen conversion system, while for storage periods beyond 1,000 h (about 40 days) the LCOS of the BESS (about 10 k€/MWh) is one order of magnitude higher than the LCOS of the hydrogen storage (about 1 k€/MWh).

Finally, the study has proven the hydrogen storage systems as a viable solution when dealing with long periods of RESs plants shutdown. Indeed, although battery storage allows to achieve a higher round-trip efficiency, it suffers several limitations when operating for long-term storage periods, not to mention the bottleneck of having energy and power strictly related which is not a limitation with hydrogen solutions as there are separated systems for storage and hydrogen or power

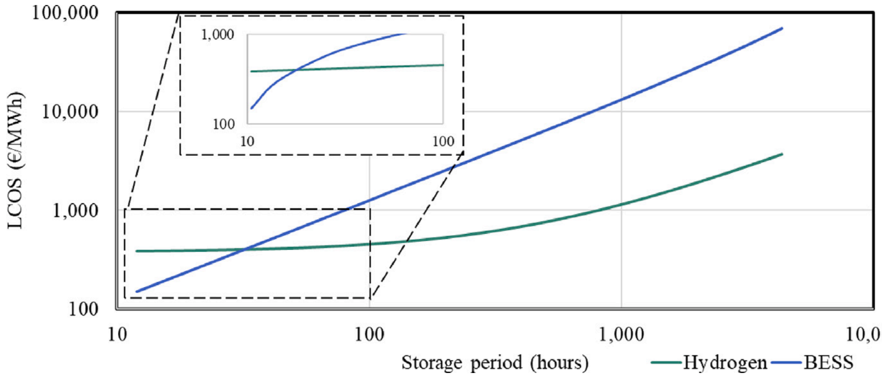


Fig. 12. LCOS as a function of the storage period.

production. In addition, batteries have a strict temperature operating range: such an aspect has not been investigated here, and it will be covered and properly addressed in future works.

CRediT authorship contribution statement

Lingkang Jin: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mosè Rossi:** Conceptualization, Data curation, Investigation, Resources, Writing – original draft, Writing – review & editing. **Andrea Monforti Ferrario:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Jacopo Carlo Alberizzi:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Massimiliano Renzi:** Writing – original draft, Writing – review & editing, Supervision. **Gabriele Comodi:** Writing – original draft, Writing – review & editing, Supervision.

Data availability

No data was used for the research described in the article.

Acknowledgements

This study was carried out within the PNRR research activities of the consortium iNEST (Interconnected North-Est Innovation Ecosystem) funded by the European Union Next-GenerationEU (Piano Nazionale di Ripresa e Resilienza (PNRR)) – Missione 4 Componente 2, Investimento 1.5 – D.D. 1058 23/06/2022, ECS_00000043). This manuscript reflects only the Authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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