Multi-objective optimization of an energy community: an integrated and dynamic approach for full decarbonisation in the European Alps

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ABSTRACT

At the local level, energy communities are at the forefront of the European Green Deal strategy offering new opportunities for citizens to get actively involved in energy markets. The scope of this study is to apply a multi-objective optimization framework to minimize both carbon dioxide emissions and total annual costs in an energy community, considering, within different constraints, a wide availability of decision variables including local renewable energy sources, sector coupling, storage and hydrogen. The methodology involves the coupling of the software EnergyPLAN with a multi-objective evolutionary algorithm, considering 2030 and 2050 as target years and modelling a set of eight types of scenarios, each consisting of 100 optimal systems out of 10,000. The case study is an energy community in the European Alps. The results show, on the one hand, the key role of sector coupling technologies such as cogeneration, heat pumps and electric vehicles in exploiting local renewable energy sources and, on the other hand, the higher costs in introducing both electricity storage to achieve a complete decarbonisation and hydrogen as an alternative strategy in the electricity, thermal and transport sectors. More specifically, it has been identified that, by 2030 a complete decarbonisation cannot be achieved considering the replacement rates of the technologies included in the Baseline 2018, but nevertheless the European target of -55% of CO2 emissions can be reached with costs similar to those of the Business As Usual trajectory, while, by 2050 a complete decarbonisation is possible with costs within 24% higher than those of the Business As Usual trajectory.

Keywords

Energy community; Energy System Integration; Renewable energy; Low-carbon economy; Multi-Objective Evolutionary Algorithm

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1. Introduction

Nowadays, energy communities are at the forefront of the EU Green Deal strategy [1] and are offering new opportunities for citizens to get actively involved in energy markets. Energy community refers to collective energy actions that foster citizens’ participation across the energy system. It has received increased attention in recent years, developing a wide range of practices to manage energy community projects. Estimates suggest that, by 2030, energy communities could own 17% of installed wind capacity and 21% of solar [2]. Moreover, by 2050, almost half of EU households are expected to be producing renewable energy [2]. The Clean Energy legislative framework [3] recognises two formal definitions of energy communities: “Citizen Energy Communities” (CECs) which is included in the revised Internal Electricity Market Directive (EU) 2019/944 [4], and “Renewable Energy Communities” (RECs) which is

Usually, developing energy plans requires a number of steps to complete: i) a baseline study to understand the current status of the energy system in the different energy sectors (electrical, thermal and transport), ii) predicting the future demands in the different energy sectors, iii) identification of local energy sources and realistic constraints, iv) designing and optimizing energy scenarios that fulfill the demands. With respect to these steps, please consider that in the software EnergyPLAN [6] (as well as in several other models), energy demand must be estimated and added as an exogenous parameter before running the model. This is indeed a limitation (sometimes) since when energy planning is developed for future years, future energy demand is indeed stochastic (random, uncertain). Hence, some models (like LEAP, GCAM and others) use endogenous energy demands (determined by the model).

The designing and optimizing step should be able to find solutions that, in a specific context, answer the following question: “How (using what technologies) is it possible to meet decarbonisation targets at the lowest transition cost?”. Finding optimal solutions requires detailed modeling of many possible energy scenarios, exploiting appropriate optimization based techniques, considering complex interactions among all the major energy sectors in a dynamic fashion (at least on an hour-by-hour basis) [7]. Concurrently, there is a move towards “smart energy system” – a concept that was introduced by Lund et al. [8] and integrates electrical, thermal and transport sectors to develop new forms of flexibility [9] and enhance RES integration [10]. The combination of a large solution space, high temporal resolution and smart energy systems means that finding optimal solutions is computationally complex and that energy system models are crucial to design energy transition pathways and identify their impacts.

A large set of energy system modelling tools is currently available, providing modelling practitioners, planners, and decision-makers with several alternatives to depict the energy system according to different technical and methodological considerations [11]. There are basically two approaches to this identification of optimal solutions; simulation and optimization. In simulation-based analyses, scenarios are user-generated and modified and rely on user experience for determining optimal solutions in terms of system composition, e.g., capacities for different types of units [12]. In optimization-based analyses, system composition is the result of a model-endogenous optimization process seeking to minimize or maximize one or more objectives, e.g., costs and CO\textsubscript{2} emissions [12]. While simulation-based analyses provide a good basis for seeing the impacts of distinct measures and thus also provide a learning experience, optimization approaches identify optimal solutions more readily – albeit without necessarily the learning experience. Johannsen et al. [13] demonstrated how simulation and optimization approaches can converge on the same optimal solution, however it requires experience.

EnergyPLAN [6], by Aalborg University, is one of the simulators developed on the concept of “smart energy system”. A survey from 2015 showed that, at that time, EnergyPLAN had been applied 95 times to simulate case studies published in the journal literature [14]. A more recent survey shows that, as of July 1st, 2022, EnergyPLAN has been applied in 315 peer-reviewed articles, and this very high application can be seen as an inferred internal validation [15]. EnergyPLAN has been used to simulate energy systems of many different countries such as Denmark (e.g. quantifying the influence of wind power and photovoltaic on future electricity market prices [16] and evaluating energy saving synergies in national energy systems [17]), Germany (e.g. exploring full energy system transition towards 100% renewable energy in 2050 [18]), Norway (e.g. defining whether district heating can affect the flexibility potential of hydropower resources [19]), Romania (e.g. modeling the national energy system and a nuclear reduction strategy [20]), Portugal (e.g. addressing renewable energy scenarios in the national electricity system [21]) and many others. EnergyPLAN has also been used in designing energy systems at regional (e.g. the Beijing-Tianjin-Hebei region in China [22] and the South West Region in Ireland [23]) to city level (e.g. Bozen-Bolzano in Italy [24] and the municipality of Aalborg in Denmark [25]), including the topic of energy communities (e.g. in the city of Alexandroupolis in Greece [26] and in the city of Rome in Italy [27]).

As a simulation model, EnergyPLAN alone is unable to directly answer the question above without expert knowledge; it generally requires the integration of an advanced optimization tool to more find emission and cost-optimized solutions. EnergyPLAN does however have the facility to integrate with other models – either
as a computational engine or in a combination. This is
demonstrated with LEAP by Bhuvanesh et al. [28],
Cantarero [29], Kiwan & Al-Gharibeh [30] and Matak
et al. [31]. EnergyPLAN has also been combined with
various MATLAB tools, by Dominkovic et al. [32],
Bamisile et al. both for China [33] and for developing
countries [34], Doepfert & Castro [35], Tomic et al. [36]
and Pupo-Roncallo et al. [37]. Other links include with
TRNSYS by De Luca et al. [38] and by Bonati et al.
[39], MATSim by Novosel et al. [40], Markal/TIMES by
Thellufsen et al. [41], Homer by Groppi et al. [42],
energyPRO by Østergaard et al. [43], MultiNode by Pfeifer
et al. [44] and Bačeković & Østergaard [45], Modest by
Lund et al. [46], DIgSILENT Power Factory dynamic
simulations by Pillai et al. [47], and a combination with
a tailor-made demand-side response model by Olkkonen
et al. [48].

Multi-objective optimization (MOO) [49] is a popular
concept in the energy domain; it is applied in different
sub-domains such as integrated conventional and renew-
able energy systems [50], integrated energy systems
considering the life cycle assessment [51], optimization
of wind-photovoltaic hybrid power systems considering
different energy storage technologies [52], solar hybrid
combined cooling, heating and power systems [53], residen-
tial apartment complexes [54] and many others.

The International Journal of Sustainable Energy
Planning and Management (IJSEPM) widely considers
the topic of multi-objective optimization. Al Hasibi [55]
explores the role of renewable energy sources in making
sustainable generation expansion planning applying an
optimization model based on two objective functions
i.e., planning costs and emissions. Roberto et al. [56]
analyzes the potential effects of integrating distributed
heat storage in an existing District Heating Network
(DHN) where the optimization model allows identifying
the optimal operation strategies of the Distributed
Energy System (DES) by accounting both economic and
environmental parameters. Singh et al. [57] considers a
multi-objective optimization approach to identify end-
use energy efficiency policy design applied to the case-
study of India; the objective functions implemented are
the maximization of the savings to investment ratio and
the maximization of the minimum deviation of green-
house gas avoided emissions/energy savings.

In 2016, Mahbub et al. [58] were the first to combine
a multi-objective evolutionary algorithm (MOEA) with
EnergyPLAN to find optimal energy scenarios. A nota-
able number of case studies have since been performed
using the same or similar framework. The case studies
range from the national scale (e.g. Italy by Prina et al.
[59] and Bellocci et al. [60], Croatia by Herc et al. [61]
and India by Laha & Chakraborty [62]) to regional (e.g.
in Italy the Province of Trento by Viesi et al. [63], the
Region of Valle d’Aosta by Bellocci et al. [64] and the
Province of South Tyrol by both Prina et al. [65] and
Vaccaro & Rocco [66] and in Austria the Region of
Niederösterreich by Prina et al. [67]), valley (e.g. in Italy
the Val di Non [68] and the Giudicarie Esteriori [69]
both by Mahbub et al.), island (e.g. Lanzarote in Spain
by Cabrera et al. [70] and Favignana in Italy by Groppi
et al. [71]) and local scales (e.g. Aalborg Municipality in
Denmark by Yuan et al. [72] and Bressanone-Brixen in
Italy by Prina et al. [73]), also including industrial facil-
ties (e.g. the Italian refinery Sonatrach Raffineria
Italiana by de Maigret et al. [74]).

The focus of this paper is the multi-objective optimi-
ization of an energy community in the European Alps for
the years 2030 and 2050, the latter considering the full
decarbonisation target. In the case study of this paper, a
number of novel contributions are added compared to
the other mentioned studies based on the already devel-
oped EnergyPLAN+MOEA framework; therefore, we
would like to present the novelty of this work as
follows:

1. Modelling and optimization is performed on a
very complex energy community. In the electrical
sector, the designing process involves several
electrical RES (PV, hydro, biogas), the use of
batteries for electricity storage and the connection
with the national grid for import and export. In the
cogeneration sector, combined heat and power
(CHP) connected with district heating (DH) and
fueled by natural gas and biomass is considered.
The larger technological variability is in the
thermal sector: energy efficiency for building
envelopes, solar thermal, solar thermal storage,
heat pumps and multiple boilers fired by oil,
liquefied petroleum gas (LPG), natural gas,
biomass and hydrogen. The transport design
covers internal combustion engine vehicles
(ICEVs), battery electric vehicles (BEVs) and
fuel cell electric vehicles (FCEVs). Hydrogen is
largely considered including electrolyzers and
storage for blending, transport and power to
power (P2P), together with fuel cells for P2P. In a
nutshell, the decision variables include electricity,
heating and transport sectors, multiple local RES and appropriate sector coupling, storage and electric grid import/export for flexibility. Taking into consideration all the decision variables, it is perhaps safe to say that this research deals with the most complex energy system modelling compared to what found in the literature.

2. Four different types of scenarios are developed both for 2030 and for 2050 (for a total of eight types of scenarios) based on different sets of constraints. Firstly, a simulation is performed with few constraints related only to local RES potentials (PV, hydro, biogas and solar thermal). Secondly, additional constraints are set on the social acceptance of biomass boilers (lower penetration), on smaller solar thermal storage and on replacement rates (linked to lifetimes). Thirdly, additional constraints are applied on the (excluded) installation of CHP connected with DH since it is not easy to invest, install and maintain DH in a mountainous area. Finally, a dedicated design process is initiated to explore the use of hydrogen as the only resource to decarbonise the thermal and transport sectors and to support electric storage. These four sets of constraints open up different possibilities to the policy makers in the energy community. A policy maker may have a vision or perception in his/her mind; therefore, he/she can explore different optimized scenarios within this vision/perception by leveraging specific constraints. To our best knowledge, this is the first attempt to perform this kind of analysis for an energy community.

Table 1 summarizes the previously described literature review relating to energy modelling based on EnergyPLAN+MOEA, comparing this work with others in terms of territorial scale, future time steps and decision variables.

The remainder of the paper is organized as follows. In Section 2, the applied methods are described. In Section 3, the case study considered is characterized. In Section 4, the results are presented and discussed. In Section 5, conclusive remarks are provided.

2. Methods

The adopted modelling framework is based on the combination of the software EnergyPLAN and a MOEA. EnergyPLAN is a freeware simulation tool of energy scenarios developed since 1999 at Aalborg University. The main purpose of EnergyPLAN, according to the developers, “is to assist in the design of national energy planning strategies with technical and economic analyses of the consequences of different choices and investments” [6]. However, even if the main target is the national-scale, EnergyPLAN is widely used also for other geographical scales as already described in the Introduction.

EnergyPLAN includes a large variety of energy technologies, both mature and novel, to support the simulation of an energy transition from a fossil-based energy system to a 100% renewable energy system. Besides its application in investigating overall energy transition strategies, EnergyPLAN can also be used to understand the role of a specific technology or type of technologies in an energy system, as example to investigate the role of storage [75] or hydrogen technologies [76].

EnergyPLAN simulates a user-defined scenario and does not make an endogenous system optimization [12]. For this reason, this software fits well to work in synergy with a MOEA that optimize output objectives modifying input decision variables.

MOEAs are utilized to solve multi-objective optimization problems in which there are “multiple contradictory objectives which have to be optimized simultaneously” [77]. Moreover, MOEAs rely on the concept of dominance of a solution; a solution is said to dominate another solution if it is strictly better in at least one objective, while at the same time not being worse in all the other objectives. Using this concept of dominance, it is possible to define as “optimal solutions” the set of non-dominated solutions that create the so-called Pareto front.

In the specific case of this work, a MOEA is coupled with EnergyPLAN that has the function to test the fitness of the solutions (energy systems) to the environment. More specifically, EnergyPLAN is used to characterize the solutions in terms of CO2 emissions and total annual costs1 and based on these two parameters there is an evaluation of the best solutions in each generation. Each solution is characterized by a specific mix of decision variables (energy technologies) and each

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1 The total annual cost is calculated by summing three different yearly costs: energy carriers cost (for the purchase of energy carriers), operating cost (or OPEX, to ensure the operation and maintenance of technologies), investment cost (or CAPEX, for the purchase of technologies). The investment cost include the interest rate (5% in this work).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Territorial scale</th>
<th>Future time steps</th>
<th>Decision variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>de Maigret et al. [74]</td>
<td>Industry</td>
<td>2025</td>
<td>PV, wind, WH ORC, biomass ORC, NG CHP, NG boiler, H2 boiler, biomass boiler, electric boiler, solar thermal, electrolyser for H2 feedstock, SMR for H2 feedstock, electrolyser for H2 boiler, petrol ICEV, diesel ICEV, BEV, battery, heat storage, H2 storage for H2 boiler, H2 storage for H2 feedstock</td>
</tr>
<tr>
<td>Mahbub et al. [58]</td>
<td>Municipality</td>
<td>2050</td>
<td>HP, CHP, PP, onshore wind, offshore wind, PV</td>
</tr>
<tr>
<td>Yuan et al. [72]</td>
<td>Municipality</td>
<td>2050</td>
<td>onshore wind, HP, IEH</td>
</tr>
<tr>
<td>Prina et al. [73]</td>
<td>Municipality</td>
<td>2010</td>
<td>PV, HP, heat storage</td>
</tr>
<tr>
<td>This work</td>
<td>Energy Community</td>
<td>2030, 2050</td>
<td>PV, hydroelectric, biogas, battery, NG CHP, biomass CHP, solar thermal, heat storage, HP, oil boiler, LPG boiler, NG boiler, H2 boiler, diesel ICEV, BEV, FCEV, electrolyser for H2 boiler and FCEV, electrolyser for P2P, fuel cell for P2P, storage for H2 boiler and FCEV, storage for P2P</td>
</tr>
<tr>
<td>Mahbub et al. [69]</td>
<td>Valley</td>
<td>2013</td>
<td>wood boiler, oil boiler, LPG boiler, GSHP, wood CHP, PV, petrol ICEV, diesel ICEV, BEV</td>
</tr>
<tr>
<td>Mahbub et al. [68]</td>
<td>Valley</td>
<td>2020, 2030, 2050</td>
<td>wood boiler, oil boiler, NG boiler, GSHP, solar thermal, wood CHP, PV, diesel ICEV, BEV</td>
</tr>
<tr>
<td>Cabrera et al. [70]</td>
<td>Island</td>
<td>2018</td>
<td>water storage, water desalination, wind, PV</td>
</tr>
<tr>
<td>Groppi et al. [71]</td>
<td>Island</td>
<td>2050</td>
<td>PV, solar thermal, battery</td>
</tr>
<tr>
<td>Prina et al. [67]</td>
<td>Regional</td>
<td>2050</td>
<td>building energy efficiency, HP, solar thermal, PV, wind, battery, electrolyser</td>
</tr>
<tr>
<td>Bellocci et al. [64]</td>
<td>Regional</td>
<td>2050</td>
<td>battery, petrol LDV, diesel LDV, electric LDV, diesel HDV, H2 HDV</td>
</tr>
<tr>
<td>Viesi et al. [63]</td>
<td>Regional</td>
<td>2030, 2050</td>
<td>solar thermal, HP, oil boiler, LPG boiler, NG boiler, biomass boiler, biogas CHP, NG CHP, hydroelectric, PV, battery, diesel ICEV, BEV, FCEV</td>
</tr>
<tr>
<td>Prina et al. [65]</td>
<td>Regional</td>
<td>2050</td>
<td>PV, biogas PP, battery, electrolyser, fuel cell PP, H2 storage, large HPs, DH thermal storage, solar thermal, building energy efficiency, individual HPs</td>
</tr>
<tr>
<td>Vaccaro &amp; Rocco [66]</td>
<td>Regional</td>
<td>not specified</td>
<td>PV, electrolyser, fuel cells, large HP, solar thermal, battery storage, H2 storage, building energy efficiency</td>
</tr>
<tr>
<td>Prina et al. [59]</td>
<td>National</td>
<td>2050</td>
<td>building energy efficiency, HP, PV, wind, pumped hydro, battery</td>
</tr>
<tr>
<td>Bellocci et al. [60]</td>
<td>National</td>
<td>a not specific medium and long-time perspective</td>
<td>building energy efficiency, HP, NG consumption, PV, onshore wind, offshore wind, diesel LDV, gasoline LDV, electric LDV</td>
</tr>
<tr>
<td>Here et al. [61]</td>
<td>National</td>
<td>multiple time steps from 2020 to 2050</td>
<td>multiple energy-generating capacities, demand response technologies and energy storage, including: onshore wind, PV, offshore wind, BEV with smart charge, H2 transport, flexible electricity demand during 24h, battery, thermal PP, H2 in industry, HE in DH for P2H, DH heating, NG heating, HP in HH, EB in HH, biomass in thermal PP</td>
</tr>
</tbody>
</table>
decision variable is characterized by some technical, economic and environmental data (type of energy carrier used, efficiency, CAPEX, OPEX, lifetime, energy carrier cost, CO₂ emission factor; see Supplementary Materials A). At the end of the process, a Pareto front is obtained in the CO₂ emissions - total annual costs space. For more details, see Figure 1 and its description in the paper by de Maigret et al. [74].

Table 2 shows the MOEA parameters used in this work, which lead to the identification of 100 optimal energy systems (on the Pareto front) out of 10,000 simulated ones. The parameter setting of a meta-heuristic algorithm, such as a MOEA, is performed experimentally. All the parameters in this work are set based on the authors’ experience of using the EnergyPLAN+MOEA framework.

3. Case Study

This section characterizes the energy system in the considered case study during a reference year called Baseline 2018. In the Baseline 2018, the local energy demand is divided into thermal, electrical and transport sectors, while also the local electrical production, 100% based on RES, is described. Moreover, the 2030-2050 future trends of energy demands are assessed based on social and energy outlooks. The final part of this section is dedicated to the description of objectives, decision variables and types of simulation scenarios. Considerations about MOEA boundaries and extra formulas (additional algorithms for model adjustment) are described in Supplementary Materials E and Supplementary Materials F.

In this work it is analysed the case study of CEIS (Consorzio Elettrico Industriale Stenico), which is a local energy cooperative founded in 1905 in the Province of Trento (Italy). CEIS produces, distributes, and sells electricity in five municipalities: Bleggio Superiore, Comano Terme, Fiavè, San Lorenzo Dorsino and Stenico. These municipalities are situated in a mountain area of 249 km² (Figure 1), with the main urban centers between 400 and 800 m.a.s.l. and a population of 8372 inhabitants in 2018² (about 80% are CEIS members).

3.1. Thermal demand in the Baseline 2018

In the CEIS area, five technologies satisfy the thermal demand for space heating (SH), hot sanitary water (HSW) and cooking in the Baseline 2018. Among these, two are based on fossil fuels, oil and LPG boilers, and three are based on RES, biomass boilers, heat pumps and solar thermal. The CEIS municipalities neither have a gas network nor a district heating (DH) network.

### Table 2: MOEA parameters used in this work.

<table>
<thead>
<tr>
<th>MOEA parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population Size</td>
<td>100</td>
</tr>
<tr>
<td>Generations</td>
<td>100</td>
</tr>
<tr>
<td>Crossover</td>
<td>SBX crossover</td>
</tr>
<tr>
<td>Crossover probability</td>
<td>0.9</td>
</tr>
<tr>
<td>Mutation</td>
<td>Polynomial mutation</td>
</tr>
<tr>
<td>Mutation probability</td>
<td>1/number of decision variables</td>
</tr>
</tbody>
</table>

² Bleggio Superiore = 1563, Comano Terme = 2962, Fiavè = 1094, San Lorenzo Dorsino = 1570 and Stenico = 1183.
The mountainous characteristics of the CEIS area mean that the cooling demand is almost negligible.

In Table 3 is reported the total thermal demand in the CEIS area divided by type of energy source and type of use in the Baseline 2018.

In Supplementary Materials B are reported the monthly and hourly profiles of both the total thermal demand and the solar thermal production during the Baseline 2018.

3.2. “Pure electrical” demand in the Baseline 2018

Hourly electricity consumption data is not available for all users of the CEIS area, only comprehensive monthly and annual data is available. Nevertheless, hourly data is available for all local electricity productions ($E_{e, prod, j}$), for heat pumps electricity consumption ($E_{e, HP, j}$, from the analysis of the previous chapter) and for electricity exchanges in import ($E_{e, imp, j}$) and export ($E_{e, exp, j}$) with the external network. It is thus possible to construct the hourly profile of “pure electrical” demand ($E_{e, demand, j}$) using the following equation:

$$E_{e, demand, j} = E_{e, prod, j} - E_{e, exp, j} + E_{e, imp, j} - E_{e, HP, j}$$

3 According to the PEAP study, the “pure electrical” demand includes all electrical demand excluding electrical demand for heat and transport counted in the corresponding sectors [33].

The “pure electrical” demand profile of the Baseline 2018 is the mean of the profiles of 2017, 2018 and 2019; the yearly value is 28.38 GWh. Please note that in the Baseline 2018 electric vehicles, electric storage and electrolyzers are considered absent.

In Supplementary Materials B are reported the monthly and hourly profiles of the “pure electrical” demand in the Baseline 2018 in the CEIS area.

3.3. Transport demand in the Baseline 2018

Two types of transport are considered in this work: vehicles circulating on the ordinary transport network and agricultural vehicles. The total energy utilized by the transport sector is the sum of the energy for petrol and diesel vehicles circulating on the ordinary transport network and for agricultural vehicles (diesel). This is summarized in Table 4.

In Supplementary Materials B are reported the monthly and hourly profiles of the transport demand in the Baseline 2018 in the CEIS area.

3.4. Total energy demand in the Baseline 2018

Figure 2 shows the total energy demand in the CEIS area in the Baseline 2018, divided into thermal, “pure electrical” and transport sectors. The total demand is equal to 141.91 GWh/year divided in 65.73 GWh/year (46%) for the transport demand, 47.80 GWh/year (34%) for the...
thermal demand and 28.38 GWh/year (20%) for the “pure electrical” demand.

In Figure 3 is reported the monthly profile of the total energy demand in the Baseline 2018 in the CEIS area. It is possible to see that there is a strong seasonal variation with higher values during the winter season related to the space heating demand.

### 3.5. Electrical production in the Baseline 2018

In the CEIS area three types of RES are exploited for electrical production: hydropower, PV and biogas. Hourly profiles of electrical production from each of these RES are provided by CEIS and are reported in Supplementary Materials B.

Overall, the CEIS electricity production in the Baseline 2018, 100% from local RES, is equal to 29.37 GWh/year, of which 65% from hydropower, 28% from PV and 7% from biogas (Figure 4). It is interesting to note how, in the Baseline 2018, electricity consumption and production are almost the same, respectively 29.04 GWh/year\(^4\) and 29.37 GWh/year. However, the non-contemporaneity between the two profiles means that an export of 5.65 GWh/year and an import of 5.33 GWh/year are recorded.

In Figure 5 is shown the CEIS monthly electricity balance in the Baseline 2018, comparing local production and local consumption. It is possible to see that there is a strong seasonal pattern with a large excess of electricity production in the summer season and a large shortage in the winter season. However, observing with an hourly resolution (e.g., year 2019 in Figure 6) it can be noted that even within the summer period there are hours of shortage as well as within the winter period there are hours of excess.

\(^4\) Including electricity for heat pumps.
3.6. Input data for the years 2030 and 2050
The 2030-2050 future trends of energy demands are assessed considering the trend of the population, the reduction of the space heating demand due to building renovations and a projection of the historical trend of “pure” electricity consumption.

The methodology is described in detail in the Supplementary Materials C for the thermal, “pure” electricity and transport sectors. Table 5 summarizes the main results.

3.7. Objectives, decision variables and types of simulation scenario
The analysis of the future optimized scenarios using the EnergyPLAN+MOEA framework is carried out by (I) defining the objectives to be optimized, corresponding to the minimization of both total annual costs and CO₂ emissions, and (II) defining the decision variables that can be modified within a certain range, between a minimum and maximum MOEA boundary. In the CEIS case study, 26 decision variables are considered (see Table 6).
including both the technologies of the Baseline 2018 and new technologies in the electrical, thermal and transport sectors, with a special focus on the sector-coupling and storage solutions required to maximize the flexibility of the energy system and the integration of local RES.

Moreover, four types of simulation scenarios, characterized by different MOEA boundaries, are considered in this work, each with two time-steps corresponding to 2030 and 2050 (see Supplementary Materials D). Overall, the goal for the 2030 short-term scenarios is a reduction of the CO\textsubscript{2} emissions of at least 55% with respect to the year 1990, whereas the goal for the 2050 long-term scenarios is the complete decarbonisation with a 100% reduction of CO\textsubscript{2} emissions.

The first type of scenario is called S1 and it is the more “free” scenario. Indeed, in this scenario there are only few constraints on some technologies. The few constraints are on the available roof surface to install PV and solar thermal panels and on the availability of the hydroelectric and biogas resources. The realization of this scenario is more theoretical than realistic as it includes the possibility of replacing all the Baseline 2018 technologies even in a short time (2030), the availability of very large amounts of biomass and the feasibility of solar thermal storage on a seasonal scale.

The second type of scenario is called S2 and presents the same constraints of S1 plus a few more. These additional constraints are (I) the social acceptance of the individual biomass boilers, (II) the possibility to install only small solar thermal storage and (III) the consideration of a replacement rate for each technology. The first additional constraint is inserted considering the realistic future propensity of the CEIS citizens not to increase the use of biomass for individual boilers, which therefore in the higher boundary maintain the same percentage as the Baseline 2018. The second additional constraint excludes the possibility of installing large solar thermal storage, keeping this solution only at the maximum bi-daily scale in individual buildings. The third additional constraint, the replacement rate, is inserted with the purpose of considering the inertia in shifting from one technological solution to the next, linked to the lifetime. Overall, S2 is a realistic scenario in the hypothesis that there will be the possibility/willingness to install CHP with DH.

The third type of scenario is called S3 and has the same constraints of the S2 but additionally it does not allow to install CHP with DH. This scenario probably represents the more realistic future of the CEIS energy system since in such a mountain area with small and scattered villages there is a low density of heat demand and this condition makes difficult to realize DH with a reasonable energy efficiency and economy.

The last type of scenario is called S4 and it is specifically considered to investigate the local hydrogen potential. Indeed, this scenario presents the same constraints of the S2 with the further limitation that hydrogen is the only source that is possible to utilize to decarbonise the thermal and the transport sectors (through hydrogen boilers and FCEV respectively). Another S4 constraint is related to the storage of electricity only through hydrogen P2P systems (not batteries). This last scenario is an “ideal scenario” to understand advantages and limitations of the hydrogen solutions.

4. Results

This section firstly presents the results in terms of energy consumption, RES, CO\textsubscript{2} emissions and costs obtained from the EnergyPLAN simulations of the Baseline 2018, Business As Usual (BAU) 2030 and BAU 2050. BAU are scenarios that maintain the same technological mix as the Baseline 2018. After, the results of the EnergyPLAN+MOEA in the four types of simulation scenarios are reported, presenting the Pareto fronts of optimized scenarios and the combination of sustainable energy technologies for each of the energy sectors. Finally, a direct comparison among the Pareto fronts of all the four types of simulation scenarios and with relevant literature is reported.

4.1. EnergyPLAN Baseline 2018, BAU 2030, BAU 2050

In terms of primary energy consumption, in the BAU scenarios of 2030 and 2050 this decreases mainly because of the reduction in the thermal demand, due to the intervention on the building envelopes, and of improved efficiencies in thermal and transport technologies. The per capita reduction of the primary energy consumption with respect to the Baseline 2018 is of 17.09% in the BAU 2030 and of 31.47% in the BAU 2050. Moreover, the reduction of the consumption of fossil fuels in the more efficient thermal and transport sectors means also that the RES share on supply increases from a value of 36.96% in the Baseline 2018 to values of 40.93% and 45.37% in the BAU 2030 and BAU 2050. Both the improvement in energy efficiency and the increase in RES share lead to a significant reduction in per capita CO\textsubscript{2} emissions: 40.34% in BAU 2030.
and 54.64% in BAU 2050, compared to 1990. However, neither BAU 2030 nor BAU 2050 are able to reach the desired CO₂ targets: respectively -55% and -100% with respect to the year 1990.

The cost of the imported energy carriers will decrease in BAU 2030 and BAU 2050 compared to the Baseline 2018 mainly because of the reduction in the thermal and transport consumptions. Concerning the fossil fuels:

- the oil cost drops from a value of 11,441 k€/year in the Baseline 2018 to 8,134 k€/year in BAU 2050
- the LPG cost drops from a value of 965 k€/year in the Baseline 2018 to 721 k€/year in BAU 2050.

On the contrary, the electrical import cost will almost triple in BAU 2050 respect to the Baseline 2018 due to the increase of the electrical demand that is caused both from the increase of the population and from the increase of the electrical consumption per capita.

The total cost of the imported energy (fossil fuels and electrical import) drops by the 9.63% in BAU 2030 and by the 30.89% in BAU 2050, with respect to the Baseline 2018, considering per capita values.

Overall, the total annual cost per capita will increase by the 4.90% in BAU 2030 and by the 5.02% in BAU 2050, with respect to the Baseline 2018. This increase is caused by an increase of the investment cost and of the operating cost.

### 4.2. EnergyPLAN+MOEA 2030-2050: “S1: all technologies and few constraints”

Considering S1 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 7 are obtained in 2030. The Pareto front, that represents the 100 optimized solutions, range between a maximum of 1.41 tons of CO₂/(inhabitant year) and a minimum of 0.01 tons of CO₂/
Diego Viesi, Md Shahriar Mahbub, Alessandro Brandi, Jakob Zinck Thellufsen

(inhabitant year), for what concerns the CO₂ emission, and between 5265 €/(inhabitant year) and 6950 €/(inhabitant year), for what concerns the total annual cost.

Some important aspects can be noted:

- for values higher than 1.41 tons of CO₂/(inhabitant year) the algorithm does not identify a contradiction between CO₂ emission reduction and total annual cost reduction, this point represents the less costly scenario for the CEIS area with a reduction of -65% of CO₂ emission compared to 1990.
- EnergyPLAN+MOEA is able to find solutions for the complete decarbonisation of the CEIS area, from the point 1.41 tons of CO₂/(inhabitant year) the slope of the Pareto front is more or less constant until the very final part, with CO₂ emissions close to zero, where there is an increase of the slope due to the introduction of more costly decarbonisation solutions.
- the Baseline 2018, the BAU 2030 and the first point on the right of the Pareto front have approximately the same total annual cost: it will be possible for the CEIS area to face the 2030 energy transition, reaching an ambitious -65% CO₂ emission target, in a cost-effective way.

In S1 2030 the decarbonisation of the thermal sector (Figure 8) is obtained through the large use of the biomass in boilers (15-25 GWh/year) and CHP (15-25 GWh/year), complemented by a very small amount of solar thermal (0-5 GWh/year). Moreover, the decarbonisation of the thermal sector is already complete in the rightmost point of the Pareto front, suggesting that there is no contradiction between reducing CO₂ emission and total annual cost. This is the most convenient and the most highly prioritized sector in which to intervene. Along the Pareto front there are no significant changes in the mix between biomass boilers, biomass CHP and solar thermal.

The transport sector (Figure 9) is crucial to further reduce the CO₂ emission. This occurs with a progressive replacement of ICEV with BEV. This replacement shows a linearity as CO₂ emission decrease, with a constant slope, as it is also constant the increase in total annual cost on the Pareto front (Figure 7). The decarbonisation of this sector is completed at around -95% of CO₂ emission.

The electric sector (Figure 10) is characterized by a wide variety of technologies. Hydro and biogas are always maximized and provide respectively 22 GWh/year and 2 GWh/year at all CO₂ emissions. A significant contribution is also made by biomass CHP with around 6 GWh/year at all CO₂ emissions. The PV production varies a lot according to the CO₂ emissions: between -65% and -95% it is mostly in the range 5-20 GWh/year, over -95% grows quickly from 20 to 40 GWh/year. This last (costly) change is done in order to completely decarbonise the electricity consumption reducing down to zero the import from the external national grid.
A behavior specular to that of the PV is also recorded with batteries (Figure 11): from -65% to -95% the use of batteries is in the range 0-2 GWh/year, then rapidly (and costly) increases up to 8 GWh/year. To reach the -100% of CO2 emission it is necessary to install a total battery power of approximately 10,000 kW - corresponding to 1666 domestic battery units of 6 kW each.

Overall, in the range from -65% to -100% CO2 emissions (Figure 12), the increase in BEVs and batteries leads to an increase in electricity demand from 35 GWh/year to 60 GWh/year. At the same time, an increase in the exchange capacity with the national grid is required from 5 to 26 MW (for export).

Considering S1 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 13 and Supplementary Materials G are obtained in 2050. The following features are highlighted:

- the Pareto front has a lower slope as the costs of the energy transition are lower
- in the thermal sector, decarbonisation takes place mainly through biomass boilers (20-30 GWh/year) and to a lesser extent through heat pumps (0-5 GWh/year), biomass CHP provides a slight contribution (0-5 GWh/year) only after -95% of CO2 emissions
- in the transport sector, the replacement of ICEVs with BEVs is confirmed and completed at around -95% of CO2 emissions
- in the electricity sector, the behavior is similar to that of S1 2030, with the exception of a lower role of biomass CHP as it is offset by better energy efficiency of BEVs and greater import (from a 2050 more decarbonized national grid).

### 4.3. EnergyPLAN+MOEA 2030-2050: “S2: all technologies, replacement rate and biomass constraint”

Considering S2 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 14 and Supplementary Materials G are obtained in 2030. The following features are highlighted:

- the Pareto front is similar to S1 2030 but does not reach the complete decarbonisation due to replacement rates that leads to residual shares of fossil sources
- in the thermal sector, decarbonisation takes place through a high use of biomass in CHP
Diego Viesi, Md Shahriar Mahbub, Alessandro Brandi, Jakob Zinck Thellufsen

(14-16 GWh/year) and boilers (10-12 GWh/year), together with a minor contribution from solar thermal (2-5 GWh/year), while the presence of heat pumps is negligible and linked to the residual replacement rate

- in the transport sector, the replacement of ICEVs with BEVs is confirmed, with full conversion upfront at -84% of CO₂ emissions
- in the electricity sector, the characteristics are the same as those of S1 2030, the only difference is the increase in PV and batteries and the decrease in import anticipated to -84%.

Considering S2 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 15 and Supplementary Materials G are obtained in 2050.

The following features are highlighted:

- the Pareto front has a lower slope, as the costs of the energy transition are lower, and reaches the complete decarbonisation, because by 2050 it is possible to replace all the fossil technologies installed in the Baseline 2018
- in the thermal sector, decarbonisation takes place mainly through biomass CHP

(10-16 GWh/year), heat pumps (8-12 GWh/year) and biomass boilers (6-8 GWh/year), while solar thermal provides a minor contribution (1-3 GWh/year)

- in the transport sector, the replacement of ICEVs with BEVs is confirmed and completed at around -95% of CO₂ emissions
- in the electricity sector, the behavior is similar to that of S1 2050, with the exception of a higher role for biomass CHP.

4.4. EnergyPLAN+MOEA 2030-2050: “S3: all technologies, replacement rate, biomass constraint, no DH”

Considering S3 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 16 and Supplementary Materials G are obtained in 2030.

The following features are highlighted:

- the Pareto front is very similar to S2 2030 and also in this case it does not reach the complete decarbonisation due to replacement rates
- in the thermal sector, considering the lack of DH solutions, decarbonisation takes place through a high use of biomass boilers (12-15 GWh/year) and heat pumps (10-14 GWh/year), together with a minor contribution from solar thermal (2-8 GWh/year)
- in the transport sector, the replacement of ICEVs with BEVs is confirmed, with full conversion upfront at -80% of CO₂ emissions
- in the electricity sector, the characteristics are the same as those of S1 and S2 2030, the only differences are (I) the lack of biomass CHP and (II) the increase in PV and batteries and the decrease in import anticipated to -80% of CO₂ emissions.
Considering S3 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 17 and Supplementary Materials G are obtained in 2050.

The following features are highlighted:

- the Pareto front has a lower slope, as the costs of the energy transition are lower, and reaches complete decarbonisation, because by 2050 it is possible to replace all the fossil technologies installed in the Baseline 2018
- in the thermal sector, decarbonisation takes place mainly through heat pumps (18-20 GWh/year) and biomass boilers (9-11 GWh/year), while solar thermal provides a minor contribution (1-3 GWh/year)
- in the transport sector, the replacement of ICEVs with BEVs is confirmed and completed at around -95% of CO2 emissions
- in the electricity sector, the behavior is similar to that of S1 and S2 2050 but without a role for biomass CHP.


Considering S4 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 18 and Supplementary Materials G are obtained in 2030.

The following features are highlighted:

- the Pareto front involves a range with higher CO2 emissions than in previous scenarios (from -40% to -75%) and is steeper, this means that the energy transition if entrusted only to hydrogen implies higher costs, lower efficiencies and lower capability to achieve high decarbonisation based on local RES
- in the transport sector, decarbonisation takes place through the full replacement of ICEVs with FCEVs
- in the electricity sector, hydro and biogas are always maximized while PV, import and export continue to increase along the entire Pareto front, with the greatest slope represented by the PV reaching on the left its maximum local potential (around 80 GWh/year); the Pareto front is interrupted when both the RES from the national electric grid and the local RES are no longer able to support the CEIS decarbonization based on hydrogen electrolysis.

Considering S4 boundaries for the EnergyPLAN+MOEA simulation, the results of Figure 19 and Supplementary Materials G are obtained in 2050.

The following features are highlighted:

- the Pareto front has a lower slope, as the costs of the energy transition are lower, and achieves...
higher decarbonisation (up to -89%), because by 2050 hydrogen technologies are more efficient and national electricity import is greener

- in the thermal sector, a partial decarbonisation takes place through a progressive replacement of natural gas boilers with hydrogen boilers (hydrogen blending as in S4 2030)
- in the transport sector, the replacement of ICEVs with FCEVs is confirmed and completed at around -86% of CO₂ emissions
- in the electricity sector, the behavior is similar to that of S4 2030 but with a higher role for the import.

4.6. EnergyPLAN+MOEA 2030-2050: comparison among types of simulation scenarios and with relevant literature

In this paragraph, the Pareto fronts of the four types of scenarios are compared in 2030 and in 2050.

Starting from 2030 (Figure 20), it can be noted that the only scenario achieving a complete decarbonisation is S1, as it does not consider a replacement rate. Instead, the presence of fossil sources in the thermal sector (oil and LPG boilers) and the lower potential for biomass boilers raises the Pareto front in S2. The S3 solution is very similar to the S2, this shows that the choice of decarbonizing the thermal sector by means of individual heat pumps has almost the same effectiveness and the same costs as with biomass CHP and DH. In all these three scenarios (S1, S2, S3) the slope of the Pareto front is low up to very high decarbonisation percentages: a wide energy transition of the CEIS area can take place at costs similar to the current and BAU ones as early as 2030. This statement is not valid for the S4 scenario: entrusting decarbonisation to hydrogen implies higher costs, lower efficiencies and lower capability to achieve high decarbonisation rates based on local RES.

By 2050 (Figure 21), the first three types of scenarios (S1, S2, S3) are able to complete the decarbonisation, as there is enough time to replace all the fossil fuel technologies of the Baseline 2018 beyond the replacement rates. These three Pareto fronts are almost superimposable. Moreover, the slopes of the Pareto fronts are lower than 2030 in all scenarios because in 2050 decrease the costs and increase the efficiencies of the key decarbonisation technologies. The disadvantages in terms of efficiencies and costs linked to hydrogen technologies remains also in 2050.

Table 9 compares the results of this case study with those of the relevant literature described in the Introduction, with a focus on the European Alps, and a coherence emerges in the following indications:

- by 2030 and 2050 ambitious decarbonisation can be achieved, up to complete, with costs similar to those of BAU
- energy costs can be shifted from fossil fuels to local technologies, networks and services
- key transformations are the energy efficiency of buildings, the use of biomass in the thermal and electrical sectors (boilers, CHP), the electrification of the thermal (HP) and the transport (BEV) sectors and a deep exploitation of the local available renewable energy potential (hydroelectric, solar, biomass, wind)
- the decarbonisation of the thermal sector is economically more convenient than the decarbonisation of the transport sector
- the integration of batteries and above all of hydrogen is particularly costly and should therefore be subordinated to energy efficiency measures and direct electrification.
Table 9: Comparison of the results of this case study with those of the relevant literature described in the Introduction, with a focus on the European Alps. For the meaning of the acronyms refer to Table 1.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Territorial scale, future time steps, decision variables</th>
<th>Main findings</th>
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</table>
| Prina et al. [73]  | Municipality 2010 PV, HP, heat storage                    | • A solution in which a part of the excess electricity production is stored and a part is sold to the grid could be cost-effective compared to ones where all the over production is stored.  
• The most cost-effective mean to perform peak shaving is given by the HPs coupled to seasonal thermal energy storage.  
• The overall energy balance clearly highlight the interest of hybrid electric-thermal applications, showing that extending the analysis of storage solutions beyond the purely electric sector can be highly beneficial. |
| This work          | Energy Community 2030, 2050 PV, hydroelectric, biogas, battery, NG CHP, biomass CHP, solar thermal, heat storage, HP, oil boiler, LPG boiler, NG boiler, H2 boiler, diesel ICEV, BEV, FCEV, electrolyser for H2 boiler and FCEV, electrolyser for P2P, fuel cell for P2P, storage for H2 boiler and FCEV, storage for P2P | • By 2030 a complete decarbonisation cannot be achieved considering the replacement rates of the technologies included in the Baseline 2018, but nevertheless the European target of -55% of CO2 emissions can be reached with costs similar to those of the BAU trajectory.  
• By 2050 a complete decarbonisation is possible with costs within 24% higher than those of the BAU trajectory.  
• Key role of sector coupling technologies such as cogeneration, heat pumps and electric vehicles in exploiting local renewable energy sources. Higher costs in introducing both electricity storage to achieve a complete decarbonisation and hydrogen as an alternative strategy in the electricity, thermal and transport sectors. |
| Mahbub et al. [69] | Valley 2013 wood boiler, oil boiler, LPG boiler, GSHP, wood CHP, PV, petrol ICEV, diesel ICEV, BEV | • The least costly scenario is 11% less costly than the reference. Moreover, all these scenarios reduce CO2 emissions.  
• It is even possible to reach zero emissions and a system that needs only 11% of external energy resources to cover all the local energy demand for electricity, thermal and transportation.  
• The optimized scenarios show economically attractive potentials for the reduction of CO2 emissions and dependency through: (1) increasing the capacity of PV, (2) maximizing the exploitation of wood and use for individual wood boilers, and (3) partial electrification of the thermal sector through HPs. The transport sector could be profoundly transformed by increasing the use of BEVs however it is currently not cost effective. |
| Mahbub et al. [68] | Valley 2020, 2030, 2050 wood boiler, oil boiler, NG boiler, GSHP, solar thermal, wood CHP, PV, diesel ICEV, BEV | • It will be less costly to introduce renewable energy over time.  
• In 2030 scenarios are less costly than 2020 (3–4% increase of cost with respect to RS2008 and 12–13% cost reduction with respect to RS2030). All the fossil-fuel based boilers are recommended to be replaced by GSHPs and wood boilers. A small number of BEVs are introduced depending on the scenarios.  
• In 2050 GSHPs produces most of the required heat to meet the demands. Wood CHPs and boilers compensate each other in term of heat productions as well. The transportation sector is completely transformed by the introduction of BEVs. |
| Prina et al. [67]  | Regional 2050 building energy efficiency, HP, solar thermal, PV, wind, battery, electrolyser | • The key transformations are the energy efficiency of buildings, the electrified transport sector and a deep exploitation of the renewable energy potential.  
• Electric mobility at high penetration cannibalizes power-to-gas due to the reduction of the available over-generation from variable renewable energy sources (VRES).  
• This transformation of the energy system is a relevant economic opportunity as a large shift from costs for fossil fuels to investments in on place technologies and infrastructures is taking place. |
Diego Viesi, Md Shahriar Mahbub, Alessandro Brandi, Jakob Zinck Thellufsen

Conclusions

In this paper, an effort has been carried out for an Italian energy cooperative, called CEIS, to design decarbonisation energy scenarios for the years of 2030 and 2050. Hence, a multi-objective optimization technique with EnergyPLAN simulation model is applied to automatically find out optimal future scenarios, leading the identification of 100 optimal energy systems on the Pareto front out of 10,000 simulated ones, in a reasonable computational time of about 5 hours. In this study, the optimization process deals with a very complex energy system, which include electrical, thermal and transport sectors, several local RES, sector coupling, storage and hydrogen technologies, that verifies the capabilities of the optimization algorithm.

Therefore, the novelty of this paper is the modeling of future energy scenarios for energy communities with a tool that includes hourly profiles, smart integration of multiple energy sectors and storage options, coupling of a multi-objective optimization and consideration of transition paths. All together these aspects are innovative considering that the usual energy scenario modeling is based on yearly balances, ignore smart sector coupling and miss proper optimization.

Different policy visions are formulated as decision bounding variables and this approach open up a very large number of decision possibilities to the local policy makers. The results show that by 2030 a complete decarbonisation cannot be achieved considering the replacement rates of the technologies included in the current Baseline 2018, but nevertheless the European target of
-55% of CO₂ emissions can be reached with costs similar to those of the BAU trajectory. By 2050 a complete decarbonisation is possible with costs within 24% higher than those of the BAU trajectory. More specifically, from a technological point of view, the results show, on the one hand, the key role of sector coupling technologies such as cogeneration, heat pumps and electric vehicles in exploiting local renewable energy sources and, on the other hand, the higher costs in introducing both electricity storage to achieve a complete decarbonisation and hydrogen as an alternative strategy in the electricity, thermal and transport sectors.

The economic analysis is based on the input data defined during the elaboration of this study (2021, see Supplementary Materials A), data which, as regards the item “energy carriers cost”, has been literally distorted in recent months following the Russia-Ukraine crisis. It is clear that the increase in the cost of fossil fuels entails an economically more attractive energy transition and the contradiction between a decrease in the total annual cost and a decrease in CO₂ emissions can completely disappear. However, this study confirms the key role of an energy system integration approach: linking sectors will allow a better cost-effective optimization of the energy system as a whole, rather than decarbonising and making separate efficiency gains in each sector independently, and this is also valid with high costs of fossil fuels.

References


Multi-objective optimization of an energy community: an integrated and dynamic approach for full decarbonisation in the European Alps


