International Journal of Sustainable Energy Planning and Management Vol. 38 2023 8–29

International Journal of
Sustainable Energy Planning and Management

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

Diego Viesi[a*], Md Shahriar Mahbub[b], Alessandro Brandi[a], Jakob Zinck Thellufsen[c], Poul Alberg Østergaard[c], Henrik Lund[c], Marco Baratieri[d], Luigi Crema[a]

[a]*Fondazione Bruno Kessler (FBK), Via Sommarive 18, 38123 Povo (TN), Italy*
[b]*Ahsanullah University of Science & Technology (AUST), Love Road 141&142, Tejgaon Industrial Area, Dhaka-1208, Bangladesh*
[c]*Aalborg University, Rendsburggade 14, DK-9000 Aalborg, Denmark*
[d]*University of Bozen-Bolzano, Faculty of Science and Technology, Universitätsplatz 5 - Piazza Università, 5, 39100 Bozen-Bolzano (BZ), Italy*

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 CO_2 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

http://doi.org/10.54337/ijsepm.7607

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

---

*Corresponding author – e-mail: viesi@fbk.eu included in the revised Renewable Energy Directive (EU) 2018/2001 [5]. These two EU legislative documents provide an enabling legal framework for collective citizen participation in the energy system.

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_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 renewable 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], residential 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 greenhouse 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 notable 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 Bellocchi 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 Bellocchi 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 facilities (e.g. the Italian refinery Sonatrach Raffineria Italiana by de Maigret et al. [74]).

The focus of this paper is the multi-objective optimization 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 developed 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 CO_2 emissions and total annual costs[1] 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

---

[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 1: Literature review on energy modelling based on EnergyPLAN+MOEA, comparison on territorial scale, future time steps and decision variables. Abbreviations used: BEV = Battery Electric Vehicle, CHP = Combined Heat & Power, DH = District Heating, EB = Electric Boiler, EV = Electric Vehicle, FCEV = Fuel Cell EV, GSHP = Ground Source Heat Pump, HDV = Heavy Duty Vehicle, HH = Households Heating, HP = Heat Pump, ICEV = Internal Combustion Engine Vehicle, IEH = Industrial Excess Heat, LDV = Light Duty Vehicle, LPG = Liquefied Petroleum Gas, NG = Natural Gas, ORC = Organic Rankine Cycle, PHS = Pumped Hydro Storage, PP = Power Plant, PV = Photo-Voltaic, P2H = Power to Heat, P2P = Power to Power, SMR = Steam Methane Reforming, WH = Waste Heat.

Reference	Territorial scale	Future time steps	Decision variables
de Maigret et al. [74]	Industry	2025	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
Mahbub et al. [58]	Municipality	2050	HP, CHP, PP, onshore wind, offshore wind, PV
Yuan et al. [72]	Municipality	2050	onshore wind, PV, HP, IEH
Prina et al. [73]	Municipality	2010	PV, HP, heat storage
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
Mahbub et al. [69]	Valley	2013	wood boiler, oil boiler, LPG boiler, GSHP, wood CHP, PV, petrol ICEV, diesel ICEV, BEV
Mahbub et al. [68]	Valley	2020, 2030, 2050	wood boiler, oil boiler, NG boiler, GSHP, solar thermal, wood CHP, PV, diesel ICEV, BEV
Cabrera et al. [70]	Island	2018	water storage, water desalination, wind, PV
Groppi et al. [71]	Island	2050	PV, solar thermal, battery
Prina et al. [67]	Regional	2050	building energy efficiency, HP, solar thermal, PV, wind, battery, electrolyser
Bellocchi et al. [64]	Regional	2050	battery, petrol LDV, diesel LDV, electric LDV, diesel HDV, H2 HDV
Viesi et al. [63]	Regional	2030, 2050	solar thermal, HP, oil boiler, LPG boiler, NG boiler, biomass boiler, biogas CHP, NG CHP, hydroelectric, PV, battery, diesel ICEV, BEV, FCEV
Prina et al. [65]	Regional	2050	PV, biogas PP, battery, electrolyser, fuel cell PP, H2 storage, large HPs, DH thermal storage, solar thermal, building energy efficiency, individual HPs
Vaccaro & Rocco [66]	Regional	not specified	PV, electrolyser, fuel cells, large HP, solar thermal, battery storage, H2 storage, building energy efficiency
Prina et al. [59]	National	2050	building energy efficiency, HP, PV, wind, pumped hydro, battery
Bellocchi et al. [60]	National	a not specific medium and long-time perspective	building energy efficiency, HP, NG consumption, PV, onshore wind, offshore wind, diesel LDV, gasoline LDV, electric LDV
Herc et al. [61]	National	multiple time steps from 2020 to 2050	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, HP in DH for P2H, DH heating, NG heating, HP in HH, EB in HH, biomass in thermal PP
Laha & Chakraborty [62]	National	2030	rooftop PV, utility-scale PV, concentrated solar power, onshore wind, offshore wind, dammed hydro, river hydro, biomass PP, nuclear PP, coal PP, battery, PHS

decision variable is characterized by some technical, economic and environmental data (type of energy carrier used, efficiency, CAPEX, OPEX, lifetime, energy carrier cost, CO_2 emission factor; see Supplementary Materials A). At the end of the process, a Pareto front is obtained in the CO_2 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.

Table 2: MOEA parameters used in this work.

MOEA parameter	Value
Population Size	100
Generations	100
Crossover	SBX crossover
Crossover probability	0.9
Mutation	Polynomial mutation
Mutation probability	1/number of decision variables

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 km^2 (Figure 1), with the main urban centers between 400 and 800 m.a.s.l. and a population of 8372 inhabitants in 2018[2] (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.

---

[2] Bleggio Superiore = 1563, Comano Terme = 2962, Fiavè = 1094, San Lorenzo Dorsino = 1570 and Stenico = 1183.

Figure 1: On the left, in red, the Province of Trento, in the north-east of Italy. On the right, the area served by CEIS. Source [78] [79].

Table 3: Total thermal demand in the CEIS area divided by type of energy source and type of use in the Baseline 2018. Q_{SH} = thermal demand for space heating, Q_{HSW} = thermal demand for hot sanitary water, $Q_{COOKING}$ = thermal demand for cooking.

	Subdivision of consumptions in CEIS (GWh/year)					
	Oil	LPG	Wood	Heat pumps	Solar thermal	Total
Q_{SH}	11.60	6.74	15.48	1.50	0.78	36.10
Q_{HSW}	6.23	1.55	0.00	0.35	0.18	8.31
$Q_{COOKING}$	0.00	0.67	2.71	0.00	0.00	3.38
Q_{TOTAL}	17.83	8.96	18.19	1.85	0.96	47.79

Table 4: Total transport demand in the CEIS area for each type of vehicle in the Baseline 2018.

	Energy for petrol vehicles (GWh/year)	Energy for diesel vehicles (GWh/year)	Energy for agricultural vehicles (GWh/year)	Total transport energy (GWh/year)
Bleggio Superiore	3.00	7.40	1.00	11.40
Comano Terme	5.95	14.67	1.49	22.11
Fiavè	2.26	5.57	0.97	8.81
San Lorenzo Dorsino	2.99	7.37	2.09	12.44
Stenico	2.52	6.21	2.25	10.97
CEIS	16.71	41.22	7.80	65.73

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[3] ($E_{e,demand,j}$) using the following equation:

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

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

---

[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].

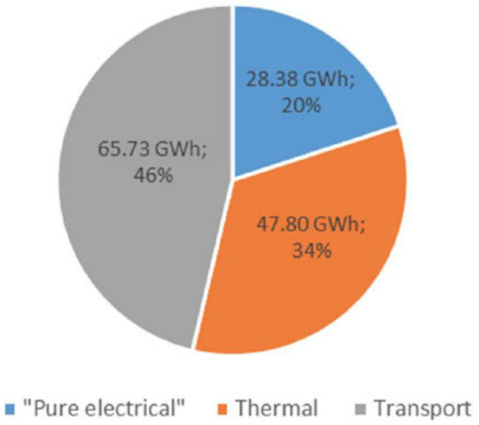

Figure 2: Total energy demand in the CEIS area in the Baseline 2018 divided into thermal, “pure electrical” and transport sectors.

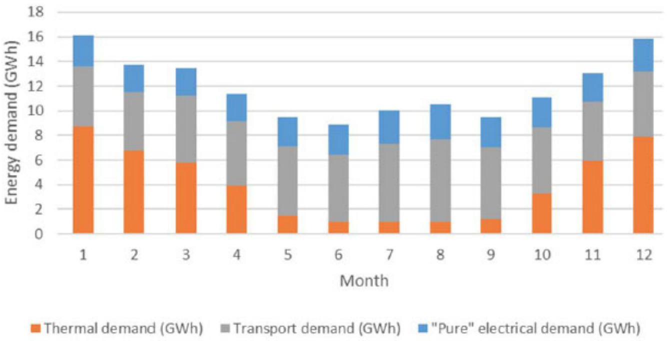

Figure 3: Monthly profile of the total energy demand in the CEIS area in the Baseline 2018 divided into thermal, “pure electrical” and transport sectors.

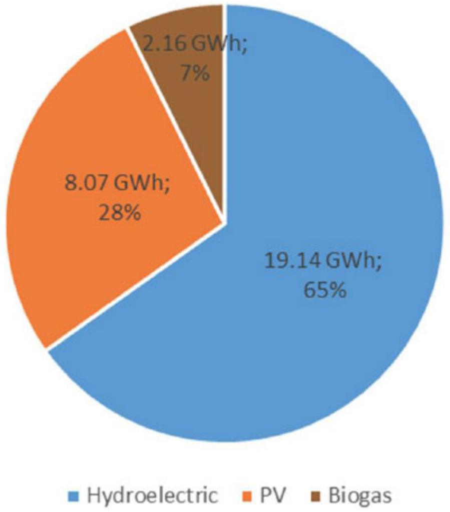

Figure 4: Total electricity production in the CEIS area in the Baseline 2018 divided in hydro, PV and biogas.

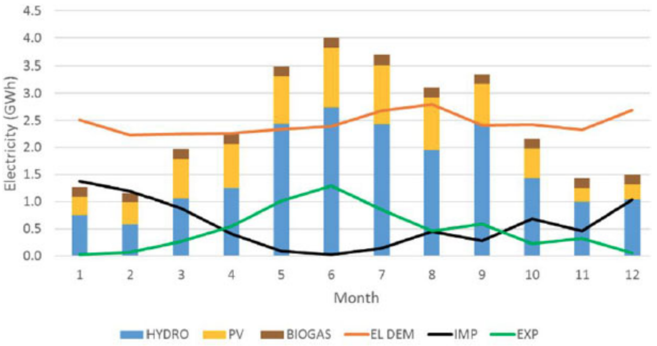

Figure 5: CEIS monthly electricity balance in the Baseline 2018: local production vs local consumption.

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.

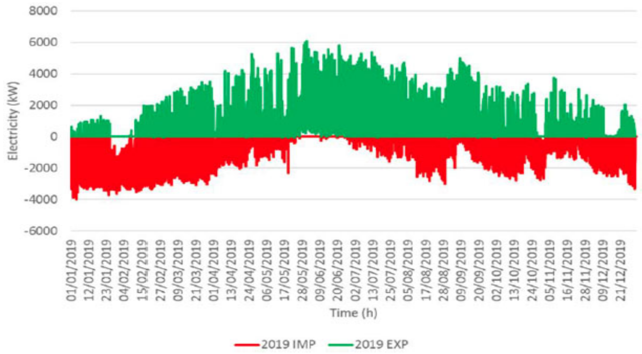

Figure 6: CEIS hourly electricity balance in the year 2019: import vs export.

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 CO_2 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)

Table 5: Analysis of the trend of the thermal, "pure" electricity and transport demands in the CEIS area. Q_{SH} = thermal demand for space heating, Q_{HSW} = thermal demand for hot sanitary water, $Q_{COOKING}$ = thermal demand for cooking, Q_{TOT} = total thermal demand, $E_{e,CEIS}$ = "pure" electricity demand, $d_{trans\ CEIS}$ = annual distance travelled by the vehicles of the CEIS area, $n_{equivalent\ vehicles}$ = number of equivalent vehicles.

Year	2018	2019	2020	2025	2030	2035	2040	2045	2050
CEIS population	8371		8426	8658	8878	9079	9246	9368	9433
Energy eff. build env. CEIS LC (GWh/year)	0.539		0.655	0.673	0.690	0.706	0.719	0.728	0.733
Q_{SH} (GWh/year)	36.11		35.03	32.63	30.01	27.16	24.07	20.74	17.22
Q_{HSW} (GWh/year)	8.30		8.36	8.59	8.81	9.01	9.17	9.29	9.36
$Q_{COOKING}$ (GWh/year)	3.38		3.40	3.50	3.59	3.67	3.74	3.79	3.81
Q_{TOT} (GWh/year)	47.79		46.79	44.72	42.41	39.84	36.98	33.82	30.39
$E_{e,CEIS}$ (GWh/year)		29.23		30.99	32.49	33.96	35.36	36.63	37.72
$d_{trans\ CEIS}$ (Mkm/year)	122.17		122.97	126.36	129.57	132.50	134.95	136.72	137.67
$n_{equivalent\ vehicles}$	9471		9532	9796	10044	10271	10461	10598	10672

Table 6: The 26 decision variables considered for the CEIS case study.

ELECTRICAL SECTOR	HYDROGEN SECTOR	CHP+THERMAL SECTOR	TRANSPORT SECTOR
Hydro (kW)	Bl-Tr Hydrogen Electrolyser (kW)	Energy eff. build. env. (GWh)	Transport el (Mkm)
PV (kW)	Bl-Tr Hydrogen Storage (MWh)	Solar thermal* (GWh)	Transport H2 (Mkm)
Biogas (kW)	P2P Hydrogen Electrolyser (kW)	Heat Pump* (GWh)	Transport diesel (Mkm)
Battery (kW)	P2P Hydrogen Fuel Cell (kW)	CHP-DH biomass* (GWh)	
Battery (MWh)	P2P Hydrogen Storage (MWh)	CHP-DH gas* (GWh)	
Import (kW)		Boiler oil* (GWh)	
Export (kW)		Boiler LPG* (GWh)	
		Boiler gas* (GWh)	
		Boiler biomass* (GWh)	
		Boiler hydrogen* (GWh)	
		Solar Heat Storage (in days of average heat demand)	

* thermal demand.

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_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_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 availably 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_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_2 emissions: 40.34% in BAU 2030

Table 7: CEIS scenarios-analysis of energy consumption, RES and CO_2 emissions.

	1990	2018	2030	2050
		BASELINE	BAU	BAU
ENERGY BALANCE				
SUPPLY (GWh/year)		157.60	137.83	120.79
SUPPLY (kWh/(inh*year))		18,827	15,525	12,806
Variation 2018 (%)			–17.54	–31.98
PRIMARY ENERGY CONS. (GWh/year)		155.44	136.69	120.05
PRIMARY ENERGY CONS. (kWh/(inh*year))		18,569	15,397	12,726
Variation 2018 (%)			–17.09	–31.47
RENEWABLE ENERGY SOURCES (RES)				
RES share (% of SUPPLY)		36.96	40.93	45.37
CO_2 EMISSIONS				
CO_2 emission (kt/year)	32.41	26.90	21.84	17.65
CO_2 emission (t/(inh*year))	4.12	3.21	2.46	1.87
Variation 1990 (%)		–22.08	–40.34	–54.64
Variation 2018 (%)			–23.44	–41.78

and 54.64% in BAU 2050, compared to 1990. However, neither BAU 2030 nor BAU 2050 are able to reach the desired CO_2 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.

Table 8: CEIS scenarios - economic analysis.

	2018	2030	2050
	BASELINE	BAU	BAU
COSTS			
Energy carriers cost (k€/year)	16,417	17,602	16,735
Oil cost (k€/year)	11,441	10,598	8,134
LPG cost (k€/year)	965	969	721
Electrical import cost (k€/year)	336	646	1,068
Total cost imp. energy (k€/year)	12,742	12,213	9,923
Total cost imp. energy (€/(inh*year))	1,522	1,376	1,052
Variation 2018 (%)		–9.63	–30.89
Operating cost (k€/year)	4,155	4,609	4,722
Investment cost (k€/year)	21,392	24,473	28,205
TOTAL ANNUAL COST (k€/year)	41,964	46,685	49,663
TOTAL ANNUAL COST (€/(inh*year))	5,013	5,259	5,265
Variation 2018 (%)		+4.90	+5.02

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 CO_2/(inhabitant year) and a minimum of 0.01 tons of CO_2/

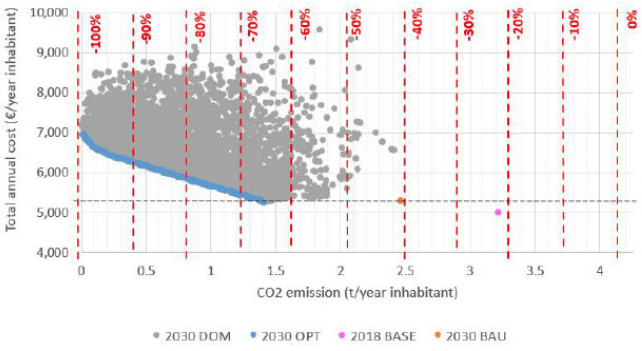

Figure 7: Pareto front of scenario S1 2030.

(inhabitant year), for what concerns the CO_2 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 CO_2/(inhabitant year) the algorithm does not identify a contradiction between CO_2 emission reduction and total annual cost reduction, this point represents the less costly scenario for the CEIS area with a reduction of -65% of CO_2 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 CO_2/(inhabitant year) the slope of the Pareto front is more or less constant until the very final part, with CO_2 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% CO_2 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 CO_2 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.

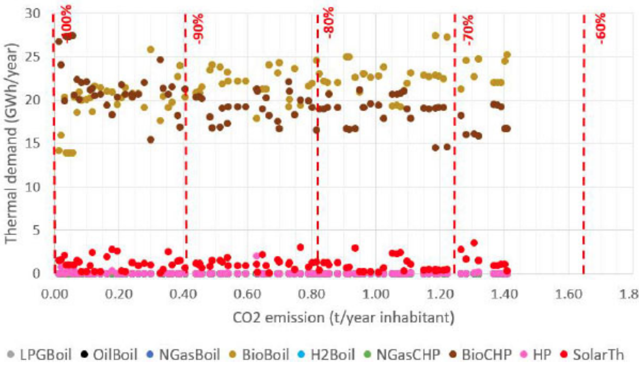

Figure 8: Thermal sector of scenario S1 2030.

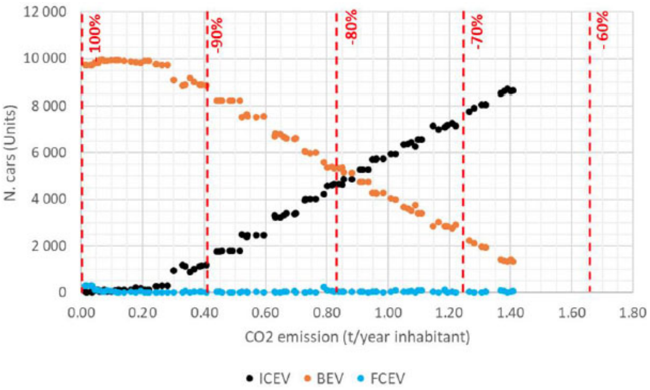

Figure 9: Transport sector of scenario S1 2030.

The transport sector (Figure 9) is crucial to further reduce the CO_2 emission. This occurs with a progressive replacement of ICEV with BEV. This replacement shows a linearity as CO_2 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 CO_2 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 CO_2 emissions. A significant contribution is also made by biomass CHP with around 6 GWh/year at all CO_2 emissions. The PV production varies a lot according to the CO_2 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.

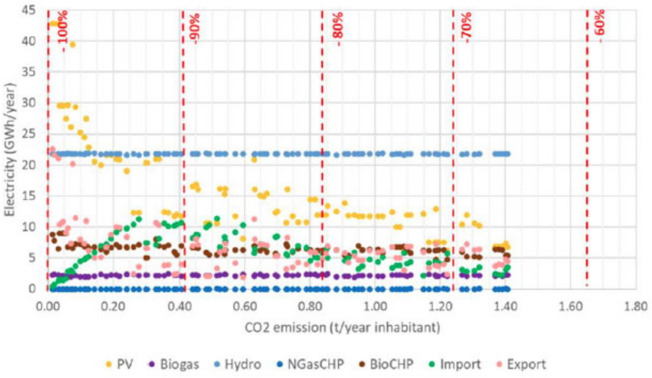

Figure 10: Electricity sector of scenario S1 2030.

Figure 11: Electricity and P2P storage use in S1 2030.

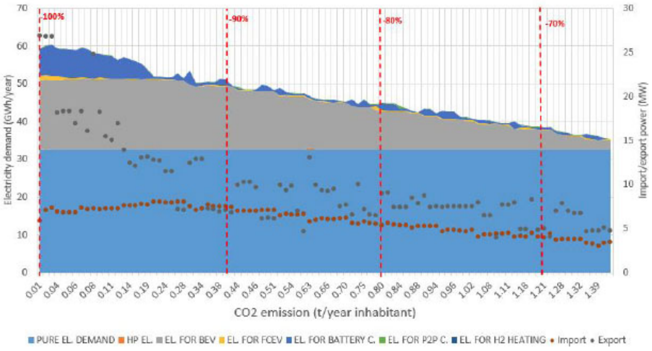

Figure 12: Electricity demand subdivision in S1 2030.

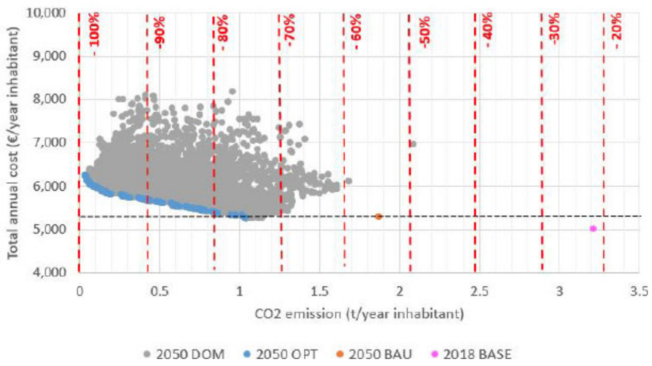

Figure 13: Pareto front of scenario S1 2050.

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 CO_2 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% CO_2 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 CO_2 emissions
- in the transport sector, the replacement of ICEVs with BEVs is confirmed and completed at around -95% of CO_2 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

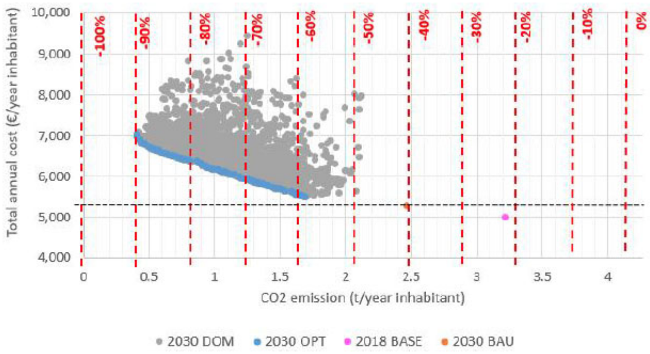

Figure 14: Pareto front of scenario S2 2030.

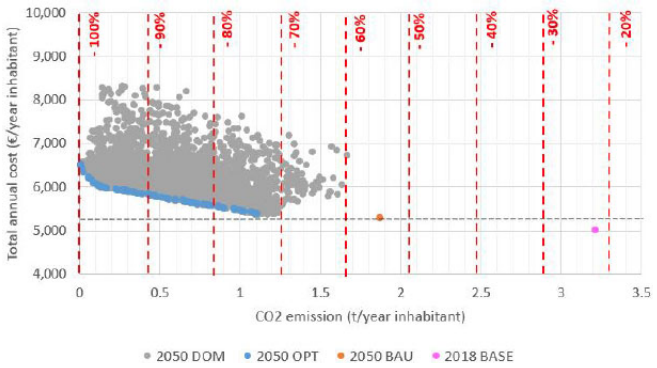

Figure 15: Pareto front of scenario S2 2050.

(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 CO_2 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)

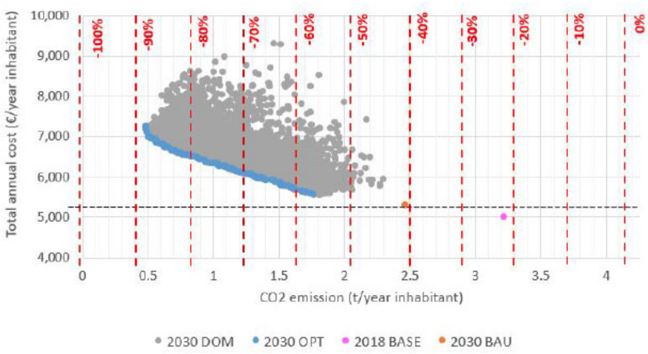

Figure 16: Pareto front of scenario S3 2030.

- in the transport sector, the replacement of ICEVs with BEVs is confirmed and completed at around -95% of CO_2 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 CO_2 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 CO_2 emissions.

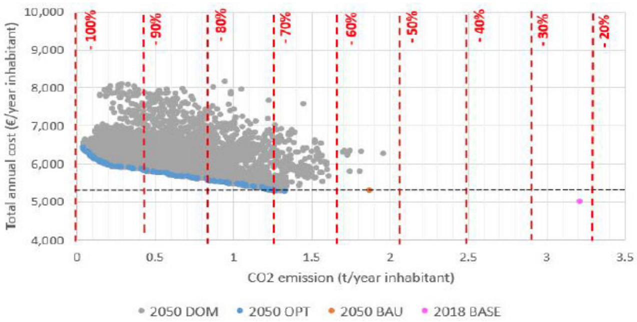

Figure 17: Pareto front of scenario S3 2050.

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 CO_2 emissions
- in the electricity sector, the behavior is similar to that of S1 and S2 2050 but without a role for biomass CHP.

4.5. EnergyPLAN+MOEA 2030-2050: "S4: hydrogen vs fossil fuels"

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 CO_2 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 thermal sector, a partial decarbonisation takes place through a progressive replacement of natural gas boilers with hydrogen boilers; this scenario would therefore suggest the construction of a new methane gas network in which to apply a blending of hydrogen, the latter rising as the desired decarbonisation increases

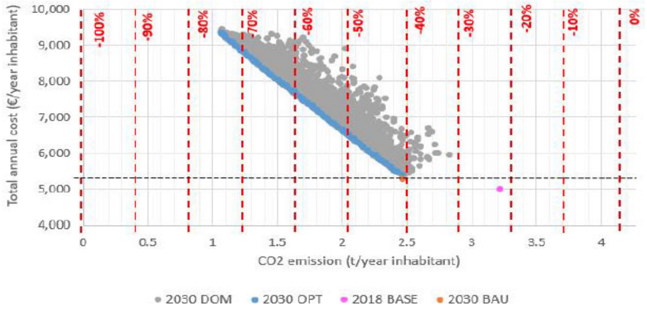

Figure 18: Pareto front of scenario S4 2030.

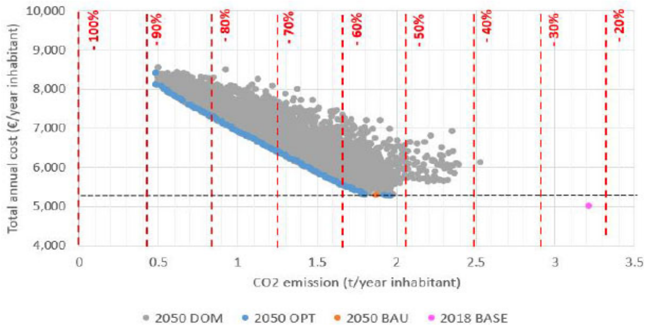

Figure 19: Pareto front of scenario S4 2050.

- 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 CO_2 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.

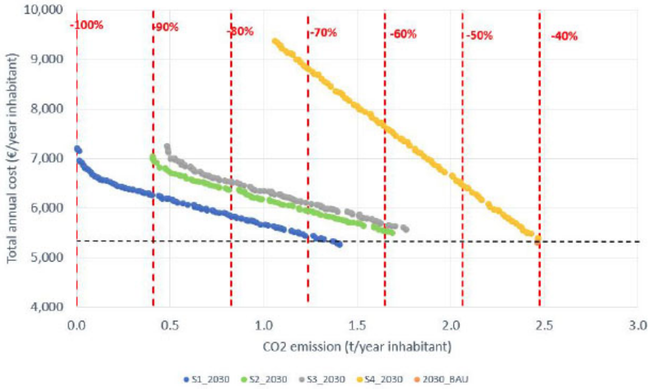

Figure 20: Comparison between 2030 Pareto fronts.

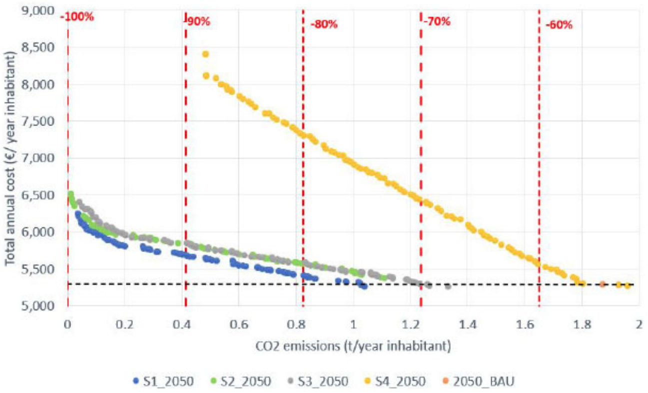

Figure 21: Comparison between 2050 Pareto fronts.

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.

Reference	Territorial scale, future time steps, decision variables	Main findings
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 CO_2 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 CO_2 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 CO_2 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.

Bellocchi et al. [64]	Regional 2050 battery, petrol LDV, diesel LDV, electric LDV, diesel HDV, H2 HDV	• Changes in quality of energy demand is foreseen by means of electrifying transport and heating sectors, including some efficiency measures and an increased PV generation. • The largest benefits are expected from the electrification of the heating sector, which can lead to CO_2 emissions reduction up to 40%, while the integration of transport electrification can bring an additional 20%. • The deployment of HP allows for a 48-50% CO_2 emissions decrease without a significant increase in additional annual costs (4-5% only) in comparison with the current case. In addition, by increasing BEV share, annual costs increase at a rate of approximately 0.7% for every percentage point of CO_2 emissions reduction. To reach higher emissions savings the deployment of H2 trucks originates a higher marginal cost.
Viesi et al. [63]	Regional 2030, 2050 solar thermal, HP, oil boiler, LPG boiler, NG boiler, biomass boiler, biogas CHP, NG CHP, hydroelectric, PV, battery, diesel ICEV, BEV, FCEV	• The integrated vision results strategic in applying sector coupling solutions among the large production from local electric RES (hydroelectric in particular), the thermal demand (through heat pumps) and the transport demand (through electric mobility). • Compared to the Baseline 2016, it is identified slight increases in total annual cost, +14% for a -90% of CO_2 emissions in 2050. • Costs breakdown highlights a significant fact: the analysed energy system can be almost free from foreign energy carriers with almost all the costs that remain in the local territory by expense on local energy carriers, operating cost and investment cost.
Prina et al. [65]	Regional 2050 PV, biogas PP, battery, electrolyser, fuel cell PP, H2 storage, large HPs, DH thermal storage, solar thermal, building energy efficiency, individual HPs	• The current system is characterized by a large export of electricity generated by hydroelectric plants. Thus, a main option for the future energy system is a shift of part of the heat and transport demand to the electricity sector. • The other main option is a reduction of the heat demand by renovating the building stock. • Increasing the energy efficiency in buildings and the installed PV capacity allows reducing the CO_2 emissions by 44% while keeping the total annual costs of the reference scenario.
Vaccaro & Rocco [66]	Regional not specified PV, electrolyser, fuel cells, large HP, solar thermal, battery storage, H2 storage, building energy efficiency	• Important role of the service sector in sustaining the other sectors towards the transition. • Significant growth of GDP (Gross Domestic Product) which could potentially be generated locally by the electronic sector and the construction sector. • Associated induced increased demand to other sectors (and sub-sectors) to sustain the outputs increases of the construction sector.

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 CO_2 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 CO_2 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

[1] EUROPEAN COMMISSION, 2019. The European Green Deal, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[2] Caramizaru, A. and Uihlein, A., 2021. Energy communities: an overview of energy and social innovation, 2020. Erişim Tarihi: Haziran, 29, https://doi.org/10.2760/180576.

[3] EUROPEAN COMMISSION, 2019. Clean energy for all Europeans, https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en.

[4] EUROPEAN UNION, 2019. Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32019L0944.

[5] EUROPEAN UNION, 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG.

[6] Lund, H., Thellufsen, J.Z., Østergaard, P.A., Sorknæs, P., Skov, I.R. and Mathiesen, B.V., 2021. EnergyPLAN–Advanced analysis of smart energy systems. Smart Energy, 1, p.100007, https://doi.org/10.1016/j.segy.2021.100007.

[7] Østergaard, P.A., 2009. Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy, 34(9), pp.1236-1245, https://doi.org/10.1016/j.energy.2009.05.004.

[8] Lund, H., Andersen, A.N., Østergaard, P.A., Mathiesen, B.V. and Connolly, D., 2012. From electricity smart grids to smart energy systems–a market operation based approach and understanding. Energy, 42(1), pp.96-102, https://doi.org/10.1016/j.energy.2012.04.003.

[9] Lund, H., Østergaard, P.A., Connolly, D. and Mathiesen, B.V., 2017. Smart energy and smart energy systems. Energy, 137, pp.556-565, https://doi.org/10.1016/j.energy.2017.05.123.

[10] Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K. and Hvelplund, F.K., 2015. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy, https://doi.org/10.1016/j.apenergy.2015.01.075.

[11] Chang, M., Thellufsen, J.Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H. and Østergaard, P.A., 2021. Trends in tools and approaches for modelling the energy transition. Applied Energy, 290, p.116731, https://doi.org/10.1016/j.apenergy.2021.116731.

[12] Lund, H., Arler, F., Østergaard, P.A., Hvelplund, F., Connolly, D., Mathiesen, B.V. and Karnøe, P., 2017. Simulation versus optimisation: theoretical positions in energy system modelling. Energies, 10(7), p.840, https://doi.org/10.3390/en10070840.

[13] Johannsen, R.M., Prina, M.G., Østergaard, P.A., Mathiesen, B.V. and Sparber, W., 2023. Municipal energy system modelling–A practical comparison of optimisation and simulation approaches. Energy, 269, p.126803, https://doi.org/10.1016/j.energy.2023.126803.

[14] Østergaard, P.A., 2015. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Applied Energy, 154, pp.921-933, https://doi.org/10.1016/j.apenergy.2015.05.086.

[15] Østergaard, P.A., Lund, H., Thellufsen, J.Z., Sorknæs, P. and Mathiesen, B.V., 2022. Review and validation of EnergyPLAN. Renewable and Sustainable Energy Reviews, 168, p.112724, https://doi.org/10.1016/j.rser.2022.112724.

[16] Sorknæs, P., Djørup, S.R., Lund, H. and Thellufsen, J.Z., 2019. Quantifying the influence of wind power and photovoltaic on future electricity market prices. Energy conversion and management, 180, pp.312-324., https://doi.org/10.1016/j.enconman.2018.11.007.

[17] Thellufsen, J.Z. and Lund, H., 2015. Energy saving synergies in national energy systems. Energy Conversion and

Management, 103, pp.259-265, https://doi.org/10.1016/j.enconman.2015.06.052.

[18] Hansen, K., Mathiesen, B.V. and Skov, I.R., 2019. Full energy system transition towards 100% renewable energy in Germany in 2050. Renewable and Sustainable Energy Reviews, 102, pp.1-13, https://doi.org/10.1016/j.rser.2018.11.038.

[19] Askeland, K., Bozhkova, K.N. and Sorknæs, P., 2019. Balancing Europe: Can district heating affect the flexibility potential of Norwegian hydropower resources?. Renewable energy, 141, pp.646-656, https://doi.org/10.1016/j.renene.2019.03.137.

[20] Gota, D.I., Lund, H. and Miclea, L., 2011. A Romanian energy system model and a nuclear reduction strategy. Energy, 36(11), pp.6413-6419, https://doi.org/10.1016/j.energy.2011.09.029.

[21] Fernandes, L. and Ferreira, P., 2014. Renewable energy scenarios in the Portuguese electricity system. Energy, 69, pp.51-57, https://doi.org/10.1016/j.energy.2014.02.098.

[22] Yuan, M., Thellufsen, J.Z., Lund, H. and Liang, Y., 2020. The first feasible step towards clean heating transition in urban agglomeration: A case study of Beijing-Tianjin-Hebei region. Energy Conversion and Management, 223, p.113282, https://doi.org/10.1016/j.enconman.2020.113282.

[23] Waenn, A., Connolly, D. and Gallachóir, B.Ó., 2014. Investigating 100% renewable energy supply at regional level using scenario analysis. International Journal of Sustainable Energy Planning and Management, 3, pp.21-32, https://doi.org/10.5278/ijsepm.2014.3.3.

[24] Menapace, A., Thellufsen, J.Z., Pernigotto, G., Roberti, F., Gasparella, A., Righetti, M., Baratieri, M. and Lund, H., 2020. The design of 100% renewable smart urb an energy systems: The case of Bozen-Bolzano. Energy, 207, p.118198, https://doi.org/10.1016/j.energy.2020.118198.

[25] Thellufsen, J.Z., Lund, H., Sorknæs, P., Østergaard, P.A., Chang, M., Drysdale, D., Nielsen, S., Djørup, S.R. and Sperling, K., 2020. Smart energy cities in a 100% renewable energy context. Renewable and Sustainable Energy Reviews, 129, p.109922, https://doi.org/10.1016/j.rser.2020.109922.

[26] Sougkakis, V., Lymperopoulos, K., Nikolopoulos, N., Margaritis, N., Giourka, P. and Angelakoglou, K., 2020. An investigation on the feasibility of near-zero and positive energy communities in the greek context. Smart Cities, 3(2), pp.362-384, https://doi.org/10.3390/smartcities3020019.

[27] Pastore, L.M., Basso, G.L., Ricciardi, G. and de Santoli, L., 2022. Synergies between Power-to-Heat and Power-to-Gas in renewable energy communities. Renewable Energy, 198, pp.1383-1397, https://doi.org/10.1016/j.renene.2022.08.141.

[28] Bhuvanesh, A., Christa, S.J., Kannan, S. and Pandiyan, M.K., 2018. Aiming towards pollution free future by high penetration of renewable energy sources in electricity generation expansion planning. Futures, 104, pp.25-36, https://doi.org/10.1016/j.futures.2018.07.002.

[29] Cantarero, M.M.V., 2018. Reviewing the Nicaraguan transition to a renewable energy system: Why is “business-as-usual” no longer an option?. Energy policy, 120, pp.580-592, https://doi.org/10.1016/j.enpol.2018.05.062.

[30] Kiwan, S. and Al-Gharibeh, E., 2020. Jordan toward a 100% renewable electricity system. Renewable Energy, 147, pp.423-436, https://doi.org/10.1016/j.renene.2019.09.004.

[31] Matak, N., Tomić, T., Schneider, D.R. and Krajačić, G., 2021. Integration of WtE and district cooling in existing Gas-CHP based district heating system–Central European city perspective. Smart Energy, 4, p.100043, https://doi.org/10.1016/j.segy.2021.100043.

[32] Dominković, D.F., Rashid, K.B.A., Romagnoli, A., Pedersen, A.S., Leong, K.C., Krajačić, G. and Duić, N., 2017. Potential of district cooling in hot and humid climates. Applied Energy, 208, pp.49-61, https://doi.org/10.1016/j.apenergy.2017.09.052.

[33] Bamisile, O., Obiora, S., Huang, Q., Okonkwo, E.C., Olagoke, O., Shokanbi, A. and Kumar, R., 2020. Towards a sustainable and cleaner environment in China: Dynamic analysis of vehicle-to-grid, batteries and hydro storage for optimal RE integration. Sustain, https://doi.org/10.1016/j.seta.2020.100872.

[34] Bamisile, O., Babatunde, A., Adun, H., Yimen, N., Mukhtar, M., Huang, Q. and Hu, W., 2021. Electrification and renewable energy nexus in developing countries; an overarching analysis of hydrogen production and electric vehicles integrality in renewable en, https://doi.org/10.1016/j.enconman.2021.114023.

[35] Doepfert, M. and Castro, R., 2021. Techno-economic optimization of a 100% renewable energy system in 2050 for countries with high shares of hydropower: The case of Portugal. Renewable Energy, 165, pp.491-503, https://doi.org/10.1016/j.renene.2020.11.061.

[36] Tomić, T., Dominković, D.F., Pfeifer, A., Schneider, D.R., Pedersen, A.S. and Duić, N., 2017. Waste to energy plant operation under the influence of market and legislation conditioned changes. Energy, 137, pp.1119-1129, https://doi.org/10.1016/j.energy.2017.04.080.

[37] Pupo-Roncallo, O., Campillo, J., Ingham, D., Ma, L. and Pourkashanian, M., 2021. The role of energy storage and cross-border interconnections for increasing the flexibility of future power systems: The case of Colombia. Smart Energy, 2, p.100016, https://doi.org/10.1016/j.segy.2021.100016.

[38] De Luca, G., Fabozzi, S., Massarotti, N. and Vanoli, L., 2018. A renewable energy system for a nearly zero greenhouse city: Case study of a small city in southern Italy. Energy, 143, pp.347-362, https://doi.org/10.1016/j.energy.2017.07.004.

[39] Bonati, A., De Luca, G., Fabozzi, S., Massarotti, N. and Vanoli, L., 2019. The integration of exergy criterion in energy planning

analysis for 100% renewable system. Energy, 174, pp.749-767, https://doi.org/10.1016/j.energy.2019.02.089.

[40] Novosel, T., Perković, L., Ban, M., Keko, H., Pukšec, T., Krajačić, G. and Duić, N., 2015. Agent based modelling and energy planning–Utilization of MATSim for transport energy demand modelling. Energy, 92, pp.466-475, https://doi.org/10.1016/j.energy.2015.05.091.

[41] Thellufsen, J.Z., Nielsen, S. and Lund, H., 2019. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. Journal of Cleaner Production, 214, pp.377-388, https://doi.org/10.1016/j.jclepro.2018.12.303.

[42] Groppi, D., Garcia, D.A., Basso, G.L. and De Santoli, L., 2019. Synergy between smart energy systems simulation tools for greening small Mediterranean islands. Renewable energy, 135, pp.515-524, https://doi.org/10.1016/j.renene.2018.12.043.

[43] Østergaard, P.A., Jantzen, J., Marczinkowski, H.M. and Kristensen, M., 2019. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renewable energy, 139, pp.904-914, https://doi.org/10.1016/j.renene.2019.02.140.

[44] Pfeifer, A., Dobravec, V., Pavlinek, L., Krajačić, G. and Duić, N., 2018. Integration of renewable energy and demand response technologies in interconnected energy systems. Energy, 161, pp.447-455, https://doi.org/10.1016/j.energy.2018.07.134.

[45] Bačeković, I. and Østergaard, P.A., 2018. Local smart energy systems and cross-system integration. Energy, 151, pp.812-825, https://doi.org/10.1016/j.energy.2018.03.098.

[46] Lund, R., Ilic, D.D. and Trygg, L., 2016. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. Journal of Cleaner Production, 139, pp.219-229, https://doi.org/10.1016/j.jclepro.2016.07.135.

[47] Pillai, J.R., Heussen, K. and Østergaard, P.A., 2011. Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios. Energy, 36(5), pp.3233-3243, https://doi.org/10.1016/j.energy.2011.03.014.

[48] Olkkonen, V., Rinne, S., Hast, A. and Syri, S., 2017. Benefits of DSM measures in the future Finnish energy system. Energy, 137, pp.729-738, https://doi.org/10.1016/j.energy.2017.05.186.

[49] Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T.A.M.T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6(2), pp.182-197, https://doi.org/10.1109/4235.996017.

[50] Xu, J., Chen, Y., Wang, J., Lund, P.D. and Wang, D., 2022. Ideal scheme selection of an integrated conventional and renewable energy system combining multi-objective optimization and matching performance analysis. Energy Conversion and Management, https://doi.org/10.1016/j.enconman.2021.114989.

[51] Chen, Y., Xu, Z., Wang, J., Lund, P.D., Han, Y. and Cheng, T., 2022. Multi-objective optimization of an integrated energy system against energy, supply-demand matching and exergo-environmental cost over the whole life-cycle. Energy Conversion and Manageme, https://doi.org/10.1016/j.enconman.2021.115203.

[52] He, Y., Guo, S., Zhou, J., Wu, F., Huang, J. and Pei, H., 2021. The quantitative techno-economic comparisons and multi-objective capacity optimization of wind-photovoltaic hybrid power system considering different energy storage technologies. Energy Conve, https://doi.org/10.1016/j.enconman.2020.113779.

[53] Li, L.L., Ren, X.Y., Tseng, M.L., Wu, D.S. and Lim, M.K., 2022. Performance evaluation of solar hybrid combined cooling, heating and power systems: A multi-objective arithmetic optimization algorithm. Energy Conversion and Management, 258, p.115541, https://doi.org/10.1016/j.enconman.2022.115541.

[54] Park, S.H., Jang, Y.S. and Kim, E.J., 2021. Multi-objective optimization for sizing multi-source renewable energy systems in the community center of a residential apartment complex. Energy Conversion and Management, 244, p.114446, https://doi.org/10.1016/j.enconman.2021.114446.

[55] Al Hasibi, R. A., 2021. Multi-objective Analysis of Sustainable Generation Expansion Planning based on Ren En Potential: A case study of Bali Province of Indonesia. International Journal of Sustainable Energy Planning and Management, 31, pp.189-210, https://doi.org/10.5278/ijsepm.6474.

[56] Roberto, R., De Iulio, R., Di Somma, M., Graditi, G., Guidi, G. and Noussan, M., 2019. A multi-objective optimization analysis to assess the potential economic and environmental benefits of distributed storage in district heating networks: A case study. I, https://doi.org/10.5278/ijsepm.2019.20.2.

[57] Singh, V.K., Henriques, C.O. and Martins, A.G., 2019. A multiobjective optimization approach to support end-use energy efficiency policy design–the case-study of India. International Journal of Sustainable Energy Planning and Management, 23. https://doi.org/10.5278/ijsepm.2408

[58] Mahbub, M.S., Cozzini, M., Østergaard, P.A. and Alberti, F., 2016. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Applied Energy, 164, pp.140-151, https://doi.org/10.1016/j.apenergy.2015.11.042.

[59] Prina MG, Fanali L, Manzolini G, Moser D, Sparber W. Incorporating combined cycle gas turbine flexibility constraints and additional costs into the EPLANopt model: The Italian case study. Energy. 2018 Oct 1;160:33-43, https://doi.org/10.1016/j.energy.2018.07.007.

[60] Bellocchi S, Manno M, Noussan M, Prina MG, Vellini M. Electrification of transport and residential heating sectors in support of renewable penetration: Scenarios for the Italian energy system. Energy. 2020 Apr 1;196:117062, https://doi.org/10.1016/j.energy.2020.117062.

[61] Herc, L., Pfeifer, A. and Duić, N., 2022. Optimization of the possible pathways for gradual energy system decarbonization. Renewable Energy, 193, pp.617-633, https://doi.org/10.1016/j.renene.2022.05.005.

[62] Laha, P. and Chakraborty, B., 2021. Low carbon electricity system for India in 2030 based on multi-objective multi-criteria assessment. Renewable and Sustainable Energy Reviews, 135, p.110356, https://doi.org/10.1016/j.rser.2020.110356.

[63] Viesi, D., Crema, L., Mahbub, M.S., Verones, S., Brunelli, R., Baggio, P., Fauri, M., Prada, A., Bello, A., Nodari, B. and Silvestri, S., 2020. Integrated and dynamic energy modelling of a regional system: A cost-optimized approach in the deep decarbonisa, https://doi.org/10.1016/j.energy.2020.118378.

[64] Bellocchi S, Guidi G, De Iulio R, Manno M, Nastasi B, Noussan M, Prina MG, Roberto R. Analysis of smart energy system approach in local alpine regions-A case study in Northern Italy. Energy. 2020 May 5:117748, https://doi.org/10.1016/j.energy.2020.117748.

[65] Prina, M.G., Cozzini, M., Garegnani, G., Manzolini, G., Moser, D., Oberegger, U.F., Pernetti, R., Vaccaro, R. and Sparber, W., 2018. Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model. Energy, 149, pp.213-221, https://doi.org/10.1016/j.energy.2018.02.050.

[66] Vaccaro, R. and Rocco, M.V., 2021. Quantifying the impact of low carbon transition scenarios at regional level through soft-linked energy and economy models: The case of South-Tyrol Province in Italy. Energy, 220, p.119742, https://doi.org/10.1016/j.energy.2020.119742.

[67] Prina, M.G., Moser, D., Vaccaro, R. and Sparber, W., 2020. EPLANopt optimization model based on EnergyPLAN applied at regional level: the future competition on excess electricity production from renewables. International Journal of Sustainable Energy Plan, https://doi.org/10.5278/ijsepm.3504 .

[68] Mahbub, M.S., Viesi, D., Cattani, S. and Crema, L., 2017. An innovative multi-objective optimization approach for long-term energy planning. Applied energy, 208, pp.1487-1504, https://doi.org/10.1016/j.apenergy.2017.08.245.

[69] Mahbub, M.S., Viesi, D. and Crema, L., 2016. Designing optimized energy scenarios for an Italian Alpine valley: the case of Giudicarie Esteriori. Energy, 116, pp.236-249, https://doi.org/10.1016/j.energy.2016.09.090.

[70] Cabrera, P., Carta, J.A., Lund, H. and Thellufsen, J.Z., 2021. Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands. Energy Conversion and Management, 235, p.113982, https://doi.org/10.1016/j.enconman.2021.113982.

[71] Groppi, D., Nastasi, B., Prina, M.G. and Garcia, D.A., 2021. The EPLANopt model for Favignana island's energy transition. Energy conversion and management, 241, p.114295, https://doi.org/10.1016/j.enconman.2021.114295.

[72] Yuan, M., Thellufsen, J.Z., Sorknæs, P., Lund, H. and Liang, Y., 2021. District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps. Energy Conversion and Management, 244, p.114527, https://doi.org/10.1016/j.enconman.2021.114527.

[73] Prina, M.G., Cozzini, M., Garegnani, G., Moser, D., Oberegger, U.F., Vaccaro, R. and Sparber, W., 2016. Smart energy systems applied at urban level: the case of the municipality of Bressanone-Brixen. International Journal of Sustainable Energy Planning an, https://doi.org/10.5278/ijsepm.2016.10.4 .

[74] de Maigret, J., Viesi, D., Mahbub, M.S., Testi, M., Cuonzo, M., Thellufsen, J.Z., Østergaard, P.A., Lund, H., Baratieri, M. and Crema, L., 2022. A multi-objective optimization approach in defining the decarbonization strategy of a refinery. Smart Energy, https://doi.org/10.1016/j.segy.2022.100076.

[75] Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z. and Sorknæs, P., 2016. Energy storage and smart energy systems. International Journal of Sustainable Energy Planning and Management, 11, pp.3-14, https://doi.org/10.5278/ijsepm.2016.11.2.

[76] Amil, C. and Yılmazoğlu, M.Z., 2022. The importance of hydrogen for energy diversity of Turkey's energy production: 2030 projection. International Journal of Hydrogen Energy, 47(45), pp.19935-19946, https://doi.org/10.1016/j.ijhydene.2022.03.274.

[77] Mahbub, M.S., Wagner, M. and Crema, L., 2016. Incorporating domain knowledge into the optimization of energy systems. Applied Soft Computing, 47, pp.483-493, https://doi.org/10.1016/j.asoc.2016.06.013.

[78] https://en.wikipedia.org/wiki/Trentino, Accessed 13/12/2022.

[79] https://www.ceis-stenico.it/, Accessed 13/12/2022.