A multi-objective optimization approach in defining the decarbonization strategy of a refinery

de Maigret, Jacopo ; Viesi, Diego; Mahbub, Md Shahriar; Testi, Matteo ; Cuonzo, Michele; Thellufsen, Jakob Zinck; Østergaard, Poul Alberg; Lund, Henrik; Baratieri, Marco; Crema, Luigi

Published in:
Smart Energy

DOI (link to publication from Publisher):
10.1016/j.segy.2022.100076

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Smart Energy 6 (2022) 100076

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

A multi-objective optimization approach in defining the decarbonization strategy of a refinery

Jacopo de Maigret [a,*], Diego Viesi [a], Md Shahriar Mahbub [b], Matteo Testi [a], Michele Cuonzo [c], Jakob Zinck Thellufsen [d], Poul Alberg Østergaard [d], Henrik Lund [d], Marco Baratieri [e], 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] Sonatrach Raffineria Italiana S.r.l, Raffineria di Augusta, Contrada Marcellino, 96011, Augusta, SR, Italy
[d] Aalborg University, Rendsburggade 14, DK-9000, Aalborg, Denmark
[e] University of Bozen-Bolzano, Faculty of Science and Technology, Universitätsplatz 5 - Piazza Università, 5, 39100, Bozen-Bolzano, BZ, Italy

A R T I C L E I N F O

Article history:
Received 1 December 2021
Received in revised form
13 February 2022
Accepted 26 March 2022
Available online 13 May 2022

Keywords:
Refining industry
Energy system integration
Renewable energy
Low-carbon economy
Multi-objective evolutionary algorithm

A B S T R A C T

Nowadays, nearly one quarter of global carbon dioxide emissions are attributable to energy use in industry, making this an important target for emission reductions. The scope of this study is hence that to define a cost-optimized decarbonization strategy for an energy and carbon intensive industry using an Italian refinery as a case study. The methodology involves the coupling of EnergyPLAN with a Multi-Objective Evolutionary Algorithm (MOEA), considering the minimization of annual cost and CO_2 emissions as two potentially conflicting objectives and the energy technologies' capacities as decision variables. For the target year 2025, EnergyPLAN + MOEA has allowed to model a range of 0–100% decarbonization solutions characterized by optimal penetration mix of 22 technologies in the electrical, thermal, hydrogen feedstock and transport demand. A set of nine scenarios, with different land use availabilities and implementable technologies, each consisting of 100 optimal systems out of 10,000 simulated ones, has been evaluated. The results show, on the one hand the possibility of achieving medium-high decarbonization solutions at costs close to current ones, on the other, how the decarbonization pathways strongly depend on the available land for solar thermal, photovoltaic and wind, as well as the presence of a biomass supply chain in the region.

1. Introduction

Since the 1998 Kyoto Protocol [1], which recognizes global warming as an anthropogenic threat to mankind, worldwide efforts have been committed towards fighting climate change. The 2015 Paris Agreement [2] reiterates the Kyoto Protocol and sets a 2 °C maximum increase of global temperature, compared to pre-industrial levels, with the pursuit of efforts to limit the increase to 1.5 °C. This latter goal was again confirmed in the more recent COP26 in Glasgow [3].

About 3.6% of global CO_2 emissions are for energy use in the chemical and petrochemical industry [4]. Nowadays there are just under 700 refineries in the world. Their energy demand consists mostly of heat, and to a lesser extent, electricity, and hydrogen. Moreover, currently their energy demand is satisfied by fossil fuel combustion [5], and most of it is produced and consumed on site. This is because petroleum refining produces unavoidable by-products, mainly refinery fuel gas (RFG) [6,7].

The great majority of refinery CO_2 emissions are attributable to the combustion of RFG for refinery heat and power systems, and thus it is particularly challenging to assess CO_2 emission abatement interventions. However, refineries are not always able to supply enough RFG to satisfy their demand of thermal power and electricity. This sees refineries importing natural gas and electricity from the national networks. If, through the implementation of mitigation technologies, this share can be reduced or avoided, multiple positive effects will be observed. Firstly, costly national network electricity and natural gas imports will be avoided. Secondly, the CO_2 emissions related to the national electric grid energy

* Corresponding author.
E-mail address: jdemaigret@fbk.eu (J. de Maigret).

https://doi.org/10.1016/j.segy.2022.100076

List of abbreviations

BAU	Business as usual
CCS	Carbon capture and storage
CCUS	Carbon capture, usage and storage
CHP	Cogeneration of heat and power
CSP	Concentrated solar power
FBK	Fondazione Bruno Kessler
GTG	Gas turbine generator
HP	High pressure
HPNG	High-pressure natural gas
HVE	High-voltage electricity
HRSG	Heat recovery steam generator
LFR	Linear Fresnel reflector
LP	Low pressure
LPNG	Low-pressure natural gas
MOEA	Multi-objective evolutionary algorithm
MP	Medium pressure
MVE	Medium-voltage electricity
ORC	Organic Rankine cycle
PUN	Prezzo unico nazionale
RES	Renewable energy sources
RFG	Refinery fuel gas
FG#45	Refinery fuel gas network, 45 psig (3.1 bar) operating pressure
SMR	Steam methane reforming
SRI	Sonatrach Raffineria Italiana
toe	tons of oil equivalent
WHB	Waste heat boiler

mix and to the combustion of natural gas will also be avoided.

The mitigation technologies that could potentially be implemented in a refinery energy system include more efficient utilization of primary energy [8], electrification of processes, substitution of fossil fuels with renewable energy sources (RES) and carbon capture usage and storage (CCUS) [9]. Berghout et al. [10] assessed the impact of different combinations of efficiency improvements, CCUS and replacement of natural gas with biomass on a refinery's energy system. The penetration of RES in the form of solar energy in the oil refinement industry is reviewed in [11]. Gray hydrogen replacement with green electrolytic hydrogen is also of relevance [12]. Its cost is becoming competitive with that of steam methane reforming (SMR) hydrogen due to the decrease of solar photovoltaic and wind power generation [13,14].

Multi-objective optimization of an energy system, based on cost and CO_2 emissions minimization, is typically applied to analyze integrated energy systems [15,16] usually at a regional level [17,18]. The specific case of the decarbonization of a refinery energy system has been carried out in [19,20]. The first study assesses the optimal degree of penetration of wind power, concentrating solar power (CSP), solar photovoltaic and import of electricity from the grid into a refinery's energy system to minimize both costs and emissions. The second study proposes a more integrated approach by also accounting for CHP. A step further is then taken when additional scenarios are simulated also accounting for thermal and electrical storage, carbon cap and trade, and CCS.

The possible combinations of sustainable technologies in the refinery's energy system are manifold. Each combination outlines a scenario defined on the one hand by investment, operational and variable costs, and on the other hand by CO_2 emissions. The identification of optimal scenarios leads to a multi-objective optimization problem. In this sense, researchers of the Fondazione Bruno Kessler (FBK) have developed an approach that sees the energy system simulation model called EnergyPLAN coupled with Multi-Objective Evolutionary Algorithm (MOEA) aimed at determining the best combination of decision variables (capacities of the energy technologies) to minimize both costs and CO_2 emissions. The case studies analyzed by FBK regard all three sectors of an energy system: electrical energy, thermal energy, and transport. The location of the case studies varies among the optimization of a city-scale energy system (Aalborg, DK [21]), sub-regional energy systems (Giudicarie Esteriori [22] and Val di Non, IT [23]), and regional level energy systems (Provincia Autonoma di Trento [24]). Analogous studies employing the EnergyPLAN + MOEA approach have been performed by. Prina et al. [25] for Italian [26] and Austrian [27] case studies, and by Bellocchi et al. [28,29] on national and regional energy systems for single (2050) and multi-step time horizons. This, however, is the first EnergyPLAN + MOEA case study dedicated to the industrial sector.

1.1. Scope, novelty and structure of the article

The scope of this study is to perform a feasibility analysis of decarbonization scenarios for the Italian refinery Sonatrach Raffineria Italiana (SRI) – Raffineria di Augusta, characterizing the cost optimal penetration of multiple sustainable energy production and storage technologies. While leaving the refinery's core activity untouched, the aim of the sustainable technologies is that of reducing or avoiding the utilization of imported electricity, natural gas, and hydrogen and their associated emissions. To find the optimal potential of the sustainable technologies in the refinery's energy system, a multi-objective optimization approach is implemented based on concurrent minimization of annual costs and emissions. The main novelty of this work lies in the implementation, for the first time, of the EnergyPLAN + MOEA approach to an industrial case study, assessing the optimal combination of 22 decision variables, (representing 22 sustainable energy technologies), including new entries such as: waste heat ORC, hydrogen steam generators/furnaces, electric steam generators/furnaces, electrolytic feedstock H_2 and SMR.

The remainder of the paper is organized as follows. In Section 2, the applied methods and materials are described. In Section 3, the results are presented and discussed. Finally, conclusions are drawn in Section 4.

2. Methods and materials

This section introduces the EnergyPLAN + MOEA energy system simulation and optimization approach followed by an in-depth description of the energy system of the case study. Within the described energy system, the areas of intervention are defined and justified. The demands of the areas of intervention are shown and put into perspective by comparing them to the overall demands of the energy system. The final part of the section is dedicated to the description of the reference model, the implementable sustainable technologies and the characterization of the simulation scenarios.

2.1. EnergyPLAN + MOEA

The RES potentially introduced in the refinery's energy system must be assessed taking their intermittent behavior, limitations in availability, and economics into account. This adds to the complexity of the problem when looking for the most effective solution in terms of annual cost and CO_2 emissions reduction. To tackle this problem effectively, an energy system simulation model is to be coupled with an optimization method.

The choice of the modeling tool fell upon the widely applied [30] and freely available EnergyPLAN energy system simulation software, developed by the Sustainable Energy Planning Research Group at Aalborg University [31,32]. The inputs of the model are hourly energy production and demands, as well as characterization of energy technologies (efficiency, CAPEX, OPEX, lifetime) and energy vectors (cost, CO_2 emission factors). The suitability of this tool is supported by its ability to simulate comprehensively all three energy sectors of an energy system (electrical, thermal and transport) [33,34], while guaranteeing an hourly resolution of the simulation [35], which allows to account for the intermittency of RES. Moreover, the interdependencies of the sectors are considered, making the software suitable to model smart energy systems. Overall, EnergyPLAN simulates energy systems and quantifies techno, environmental and economic impacts of modifications made to it.

By modeling an energy system in EnergyPLAN, a user may manually simulate a multitude of scenarios which differ from one another in the values of energy technologies capacities. While this simulation approach is good for user engagement and clarity for assessing alternatives [36], a drawback is that it is time-consuming and fails to optimally analyze a great number of scenarios.

It is therefore desirable that the EnergyPLAN software is coupled with an algorithm to automate the process and select the best scenarios thus further reducing time demands. The algorithm also has the potential to handle a large number of decision variables which generate a large search space, though advanced optimization techniques are needed in order to restrict the computational demand.

As noted, the aim of this study is twofold: minimizing annual cost and minimizing annual CO_2 emissions, therefore, the optimization problem is a multi-objective optimization problem. The family of algorithms looked into by Shahriar et al. [21] is that of the meta-heuristic optimization algorithms in a multi-objective framework, and among these the class of evolutionary algorithms was chosen. The name for the specific class of optimization methods is called multi-objective evolutionary algorithms, or MOEAs. These are inspired by natural evolution as they promote the “fittest” of the scenarios simulated.

In Fig. 1 the overall flow chart of the adopted algorithm is presented, as well as its coupling with EnergyPLAN. The algorithm starts with an initial phase that randomly initialized a number of individuals (*i.e.* scenarios). Afterward, those individuals are evaluated by using EnergyPLAN (*i.e.* individuals are simulated to calculate CO_2 emission and cost). A ranking procedure is performed to rank the evaluated individuals according to objective values. Once the ranking is performed, the algorithm checks if the stopping

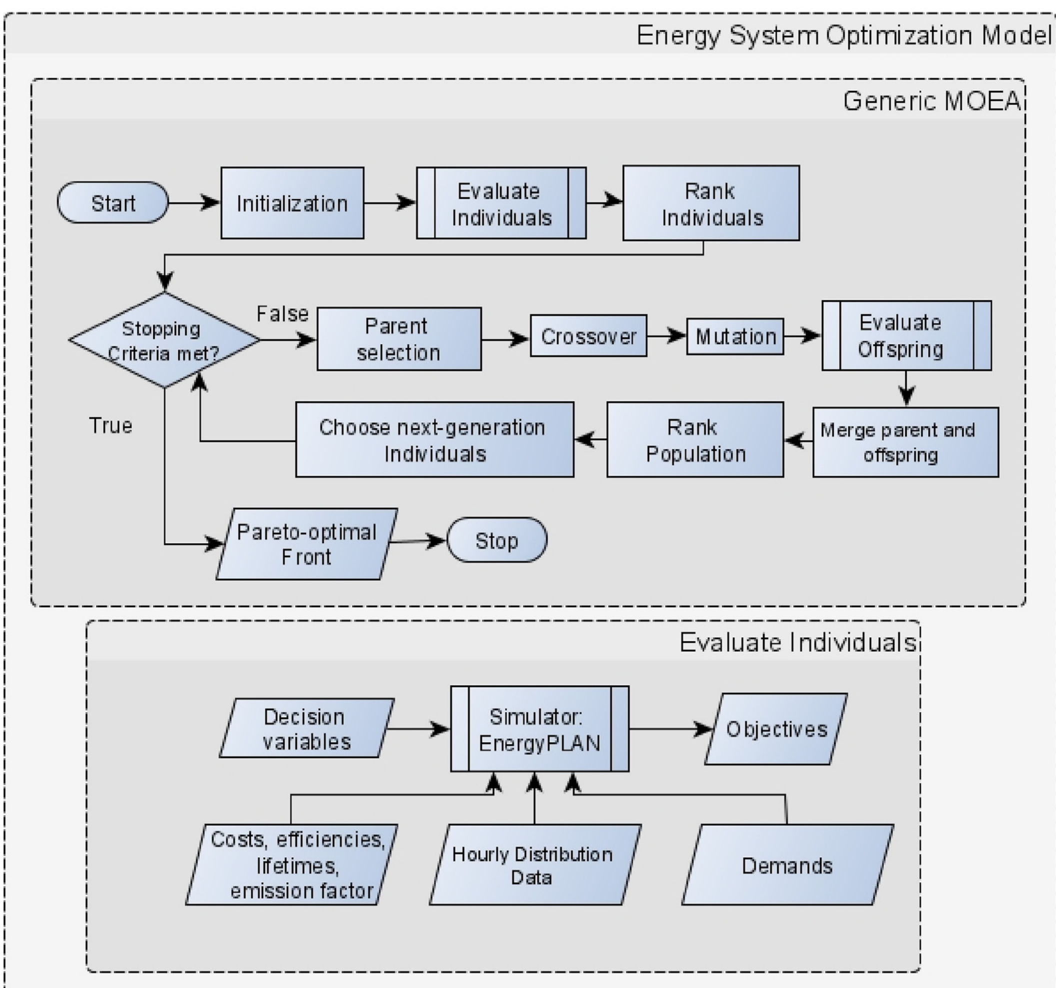

Fig. 1. Block diagram depicting the operating flow of the evolutionary algorithm coupled with EnergyPLAN as its evaluating tool.

Table 1
Energy demand and throughput of the refinery between 2014 and 2018. The maximum capacity is 14.4 Mt/year. The procedure and conversion factors to express the energy demand is that proposed by the Italian body for alternative energy (ENEA) [38] and implemented by the refinery [39].

Year	Refinery energy demand [toe]	Refinery energy demand [TWh]	Crude oil processed [t]
2014	580,341	6.75	8,231,200
2015	584,886	6.80	9,172,240
2016	611,290	7.11	9,146,716
2017	644,002	7.49	9,984,507
2018	586,492	6.82	8,405,155

criterion is met, in the case of the evolutionary algorithm the stopping criteria is defined by fixing a certain number of generations. This number is determined for the specific optimization problem and is dictated by experience (trial and error). If the stopping criterion is not met, the algorithm will proceed to the reproduction phase, which is characterized by the parent selection, crossover, and mutation. A step of choosing individuals for the next generation is performed; this step includes evaluation of offspring, merging of parents and offspring and ranking of merged population. The final result of the MOEA with two objectives to optimize is embodied in a set of optimized solutions which together form the Pareto front. It is also necessary to introduce an upper and lower limit to the values taken by the decision variables. This is done to both reduce the search space of the algorithm and to link the simulation to a real case study.

The main advantage of the approach applied in this paper, is the synergy between EnergyPLAN, which allows to define a dynamic (hourly) multi-sectorial deterministic model, and a MOEA, which enables automation of scenario simulation and efficient multi-objective optimization (both CO_2 and cost). To be more specific, in this case study the EnergyPLAN + MOEA framework is able to simulate 10,000 scenarios (after 100 generations) in only about 4 h, also taking advantage of the EnergyPLAN "spool" mode; manually simulating 10,000 scenarios would take an incalculable longer time, without the certainty of finding optimized solutions.

The use of EnergyPLAN + MOEA is intended as a high-level approach, suitable for a preliminary investigation and a starting point for a more in-depth analysis of the single sectors/components. The approach provides a general view of the potential decarbonization strategy for the refinery planning office. Moreover, EnergyPLAN is intended to model regional energy systems and to envision their possible transition pathways [37]. Utilizing it for an industrial energy system will bring the user to running into some limitations, especially in the variety of inputs. For example, different types of gas boilers and CHPs, H_2 boilers, or hydrogen by SMR are not included. This leads to the necessity of consider EnergyPLAN technologies with mediated parameters, consider EnergyPLAN technologies for other purposes (e.g. H_2 micro CHP as H_2 boiler) and add extra-formulas in the MOEA code (e.g. to enable the H_2 production both with SMR and with electrolysis, to add extra costs, and to add additional CO_2 emissions from SMR).

2.2. Case study

Sonatrach Raffineria Italiana, or SRI, is an Italian refinery situated in the south-eastern part of Sicily. It is part of a large petrochemical complex called "Polo petrolchimico siracusano". SRI is the third refinery in Italy by means of throughput, totaling an average of 9 million tons of processed raw goods per year out of a maximum capacity of almost 14.4 million tons. This refinery carries out all the major standard oil refinement processes such as atmospheric and vacuum distillation, reforming, alkylation and hydrodesulfurization.

Table 1 shows energy demand data in the period 2014–2018, together with the total amount of raw materials processed in the refinery (crude oil processed).

The year 2017 presents the highest energy consumption and throughput values.

The refinery is equipped with two gas turbine cogeneration groups (GTG), which produce electrical energy and thermal energy in the form of steam. The two gas turbines (Fig. 2) are denoted as:

- **GTG-101:** 14.75 MW of mechanical power at the shaft under nominal conditions;
- **GTG-501**: 42.7 MW of mechanical power at the shaft under nominal conditions.

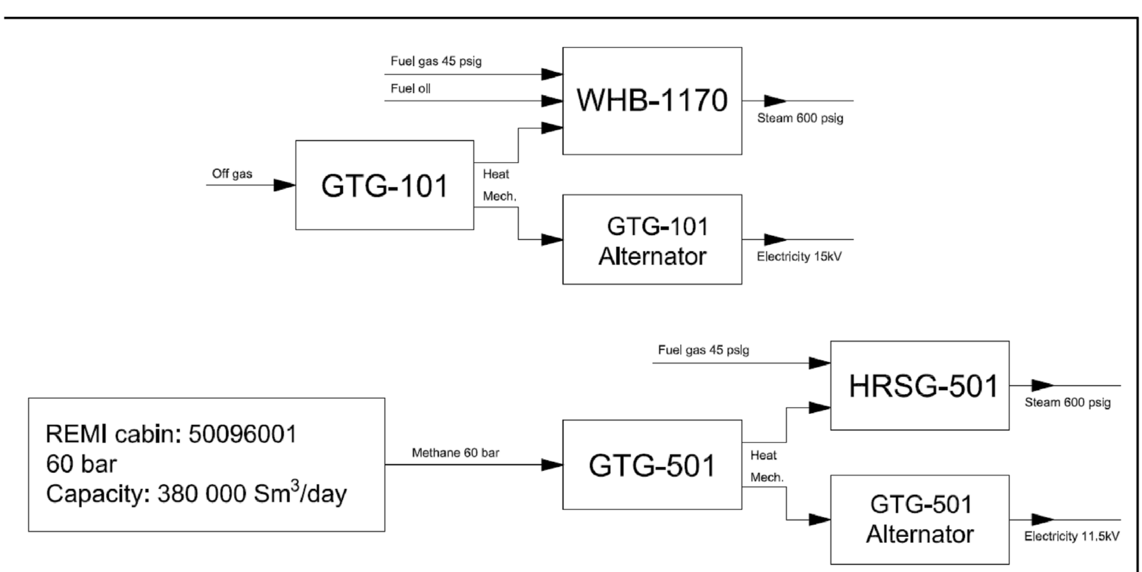

Fig. 2. Schematic representation of the cogeneration units of SRI with coupling with the steam generators. The individual fuel inputs are reported.

Table 2
Energy vectors imported into the refinery [39].

	Energy usage [MWh/year]	Energy price [€/MWh]	Energy cost [k€/year]
HPNG	973,078	24.80	24,138
LPNG	859,523	24.90	21,411
HVE	62,164	130.30	7,714
MVE	2,491	136.70	342
	[ton/year]	**[€/kg]**	**[k€/year]**
Hydrogen	3,679	1.67	6,144
	[liters/year]	**[€/liter]**	**[k€/year]**
Petrol	34,000	1.53	52
Diesel	30,000	1.40	42

Most refinery processes require thermal energy to heat refinery streams to the desired process temperature. For example, SRI's vacuum distillation towers require inlet temperatures of 420 °C and the reformer unit (R-5), of up to 530 °C. The heat is provided by the refinery's furnaces which are for the most part fueled by RFG.

The refinery's steam supply system is composed by three networks operating at three different pressures - high-, medium- and low-pressure (HP, MP, and LP). The MP and LP steam networks are equipped with venting systems which allow to vent steam into the atmosphere in case demand and supply do not match, thus protecting the networks from overpressure. HP steam is produced by three boiler steam generators and two heat recovery steam generators:

- **SG-151 & SG-1200**: boilers fueled by refinery fuel gas.
- **CO-BOILER**: boiler coupled with the catalytic cracking unit and also equipped with extra burners fueled by refinery fuel gas and fuel oil.
- **WHB-1170**: waste heat boiler coupled with the GTG-101 and also equipped with extra burners fueled by refinery fuel gas and fuel oil.
- **HRSG-501**: heat recovery steam generator coupled with the GTG-501 and also equipped with extra burners fueled by refinery fuel gas.

2.3. Import-only model (areas of intervention)

Overall, SRI is interested in the assessment of a sustainability vision for the year 2025 of its energy supply and suggested the introduction of several sustainable energy technologies to help mitigate the CO_2 emissions of the plant. However, it was made clear that the refinery throughput may not be influenced by this sustainable transition. This means that the energy supply share coming from refinery by-products (RFG, catalytic cracking coke, fuel oil) is to remain untouched.

In light of this, it has been necessary to narrow down the area of the assessment including only the imported energy carriers. The energy carriers which are imported from outside the refinery boundaries are:

- High voltage electricity (HVE);
- Medium voltage electricity (MVE);
- Low pressure natural gas (LPNG);
- High pressure natural gas (HPNG);
- SMR feedstock hydrogen;
- Petrol and diesel consumption for vehicles.

Table 2 reports the total annual quantity of the energy vectors imported in the refinery in 2017 along with the specific and overall costs associated with it.

Table 3
Energy mix and generation efficiency of the national electricity grid for the years 2017 and 2025 [43,44].

Year	Coal (%)	Oil (%)	Gas (%)	Renewable & Nuclear (%)	Efficiency (%)
2017	13.75	3.71	38.67	43.87	43
2025	0.00	1.93	44.25	53.81	51

2.3.1. High- and medium-voltage electricity

Concerning the electricity import/export, SRI is connected both to the national transmission grid (HVE) and to the local distribution grid (MVE). The annual electricity import for 2017 was 65 GWh, as reported in Table 2, for a cost of 8.1 M€. The cost of electricity includes the single national price (Prezzo Unico Nazionale, PUN [40]) and the distribution costs, [41,42].

The past and the future generation mix and efficiency of the national grid are reported in Table 3.

2.3.2. High- and low-pressure natural gas

HPNG is solely used to feed the GTG-501, which produces both high-voltage electricity and steam through the heat recovery steam generator (HRSG-501). The imported HPNG is included in the analysis in its entirety. In Table 2, the total annual consumption of HPNG is reported, equal to 973 GWh for a cost of 24.1 M€.

The thermal efficiency of the GTG-501 was not provided by the refinery. It was therefore found in literature to be 45% [45]. The electrical efficiency was estimated as 32% by assessing the HPNG input distribution and the electrical energy production distribution.

The main function of LPNG is the balancing of the refinery fuel gas network operating a pressure of 3.1 bar, or 45 psig (denoted as FG#45 in refinery documents). However, a small part (not specified by the refinery) is destined to refinery processes as feedstock (not combustible fuel). This is a refinery production process and will be excluded from the assessment. In Table 2, the total annual consumption of LPNG is reported, equal to 860 GWh for a cost of 21.4 M€. The annual ratio of LPNG to refinery fuel gas in the FG#45 is 1–5.

2.3.3. Feedstock hydrogen and petrol/diesel for vehicles

The hydrogen consumption as feedstock and the petrol/diesel consumption for vehicles are included in the assessment in their entirety. This because all the 124 GWh/year of hydrogen consumed as feedstock by the refinery is imported from a nearby Air Liquide SMR plant, and also all the 0.33 GWh/year of petrol and 0.35 GWh/year of diesel consumed by the vehicles are acquired from the outside market. The costs are equal to 6.1 M€ for the import of hydrogen, 52 k€ for the import of petrol and 42 k€ for the import of diesel.

2.3.4. Steam generators and process heat furnaces

Out of the five steam generators, the SG-151 and the SG-1200 are entirely fueled by the FG#45 network. The annual hourly distribution of consumption from this network has been provided for both steam generators and, therefore, the LPNG consumption could be derived. Differently from the furnaces, the refinery did not provide annual hourly averaged values for the boiler efficiency. Therefore, a value of 93% was taken from literature [45]. In Table 4 the annual LPNG consumption and the relative steam productions are reported.

The approach taken to extrapolate the LPNG contribution for the WHB-1170, the HRSG-501 and the CO-Boiler is analogous to the one take for the SG-151 and SG-1200. The hourly distributions of FG#45 mass flow rate consumptions are provided by the refinery, as well as the lower heating value (LHV). The average monthly efficiency of

Table 4
Yearly demand of low-pressure natural gas (LPNG) for steam generator and aggregated by refinery furnaces. All thermal energy generator systems are co-fired by natural gas as well as by other by-product fuels. The values of steam and heat generated are therefore only relative to the natural gas share of the fuel.

	LPNG demand [MWh/year]	Steam from LPNG share [MWh/year]
SG-151	106,671	99,204
SG-1200	46,160	42,929
WHB-1170	24,586	22,865
HRSG-501	49,746	46,264
CO-Boiler	8,872	8,250
	LPNG demand [MWh/year]	**Heat produced [MWh/year]**
Furnaces	623,500	519,600

93% was used [45]. The annual LPNG consumption and the relative steam productions are reported in Table 4.

Similarly to the steam generators, refinery furnaces are fed by the FG#45 network, with also a small contribution by the fuel oil network. The content of the fuel oil network is locally produced as a by-product of the refinery processes and therefore is not included in the assessment. The monthly LPNG share percentage was isolated from the total fuel input distribution, and through the efficiency (provided by the refinery, about 83%) it was possible to obtain the heat contribution of the LPNG share. In Table 4 the annual LPNG consumption and the relative heat production are reported.

2.3.5. Overview

Reported in Fig. 3 is the percentage of the total energy demand included in the import-only model. The thermal demand is embodied both in the form of steam and process heat, generated by steam generators and refinery furnaces respectively. Overall, attributable to import are: 25% of steam, 17% of furnace process heat, 86% of electricity and 100% of SMR hydrogen and petrol/diesel for refinery vehicles. Overall, the import-only model accounts for 25% of the refinery's energy demand. Fig. 4 schematically represents the refinery import and transformation of energy vectors.

2.4. Baseline 2017

The first step in the decarbonization assessment was to generate in EnergyPLAN the import-only model described in the previous section. Having characterized the 2017 model with the data provided by the refinery, EnergyPLAN produced results in terms of annual cost and CO_2 emissions, the values of which were compared with the refinery provided data as to validate the model. For the specific case study of the SRI refinery, the EnergyPLAN input data used is reported in Fig. 5.

2.5. Sustainability vision 2025

The year 2025 was assumed as the target time in which the sustainable interventions on the refinery could take place. This decision is due both to the planning steps necessary to achieve this transition and to the fact that the refinery has announced an extraordinary plant downtime in 2025. The Business-As-Usual (BAU) 2025 energy system is characterized by the same demands and technological mix of 2017 but with the costs, efficiencies, lifetimes and national electric grid characteristics foreseen for the year 2025. The BAU 2025 was generated to provide a term of comparison between sustainable scenarios and the refinery's performance if no actions are taken.

2.5.1. Implemented sustainable technologies

The 2025 decarbonized scenarios, which characterize the sustainability vision, are defined by the penetration of several sustainable technologies in the refinery energy system, for energy generation and energy storage (see Table 5).

These are the technologies that may potentially be implemented in the 2025 sustainability vision. Each technology was characterized in terms of yearly and hourly production, efficiency, CAPEX and OPEX. Technologies such as electric steam generators and furnaces, waste heat recovery organic Rankine cycle (ORC) turbine, electrolytic hydrogen, hydrogen blending and battery electric vehicles, represent coupling among sectors which made EnergyPLAN

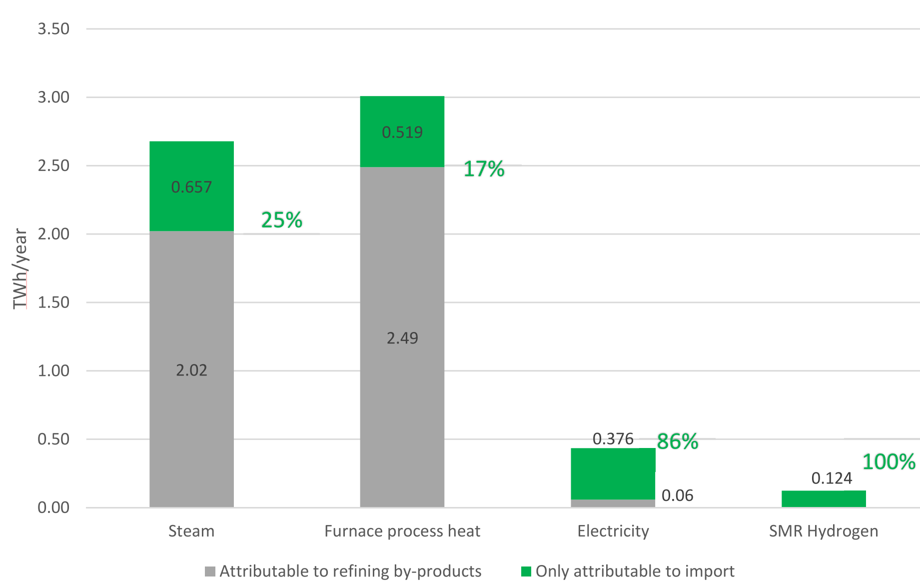

Fig. 3. Total annual energy demand of the SRI refinery with indication in green of the imported share included in the analysis Total petrol and diesel demands of 0.68 GWh/year are not shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

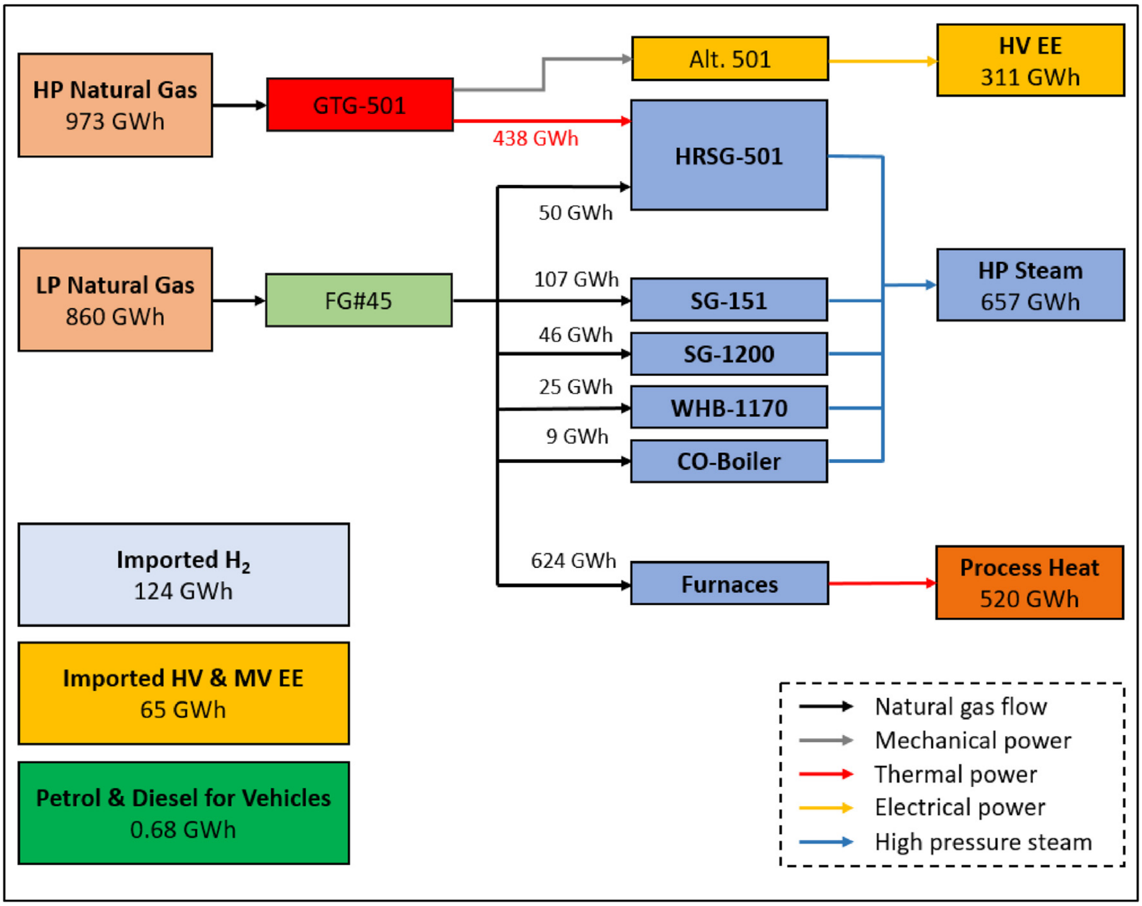

Fig. 4. Import and transformation of energy vectors. FG#45 refers to the refinery fuel gas network operating a pressure of 45 psig.

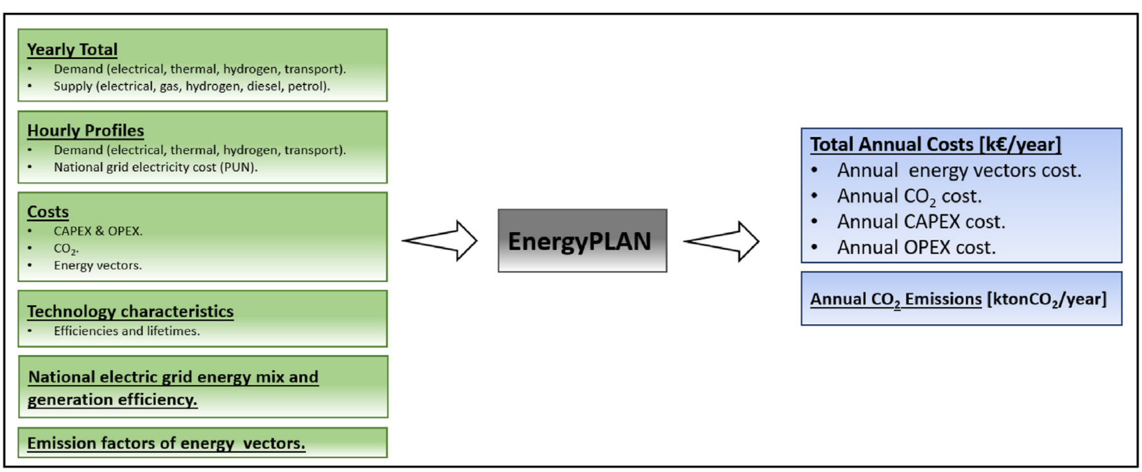

Fig. 5. EnergyPLAN inputs for the SRI refinery case study (green) and the outputs (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

suitable to simulate such an energy system. Having characterized the sustainable technologies, their capacities are the so-called decision variables in the EnergyPLAN + MOEA approach.

2.6. Simulation scenarios

In order for the EnergyPLAN + MOEA model to provide a more ample and complete view on the decarbonization interventions, a total of nine scenarios were simulated. Recalling the functioning of the evolutionary algorithm used for the two-objective optimization, the values which can be taken by the decision variables are limited to a user specified range (boundaries). The upper and lower boundaries, set on the algorithm's search space, help to confine the domain of the decision variables but may also be used to model different scenarios.

In this study, this characteristic was used to generate three macro-categories (S1, S2 and S3) defined by increasing land availability for the installation of renewable energy technologies, more

Table 5
Sustainable technologies implemented in the assessment of the SRI sustainability vision, grouped by energy sector. All technologies were characterized in terms of CAPEX, OPEX, lifetime and efficiency. Concentrating solar thermal, solar photovoltaic and wind power were also characterized for the specific geographical location.

Energy Sector				
Thermal	**Electrical**	**Storage**	**Hydrogen**	**Transport**
Concentrating solar thermal	Solar photovoltaic	Thermal storage	Electrolytic hydrogen	Battery electric vehicles
Hydrogen blending	Wind power	Electrical storage		
Biomass steam generators and furnaces	Biomass ORC	Hydrogen storage		
Electric steam generators and furnaces	Waste heat recovery ORC			

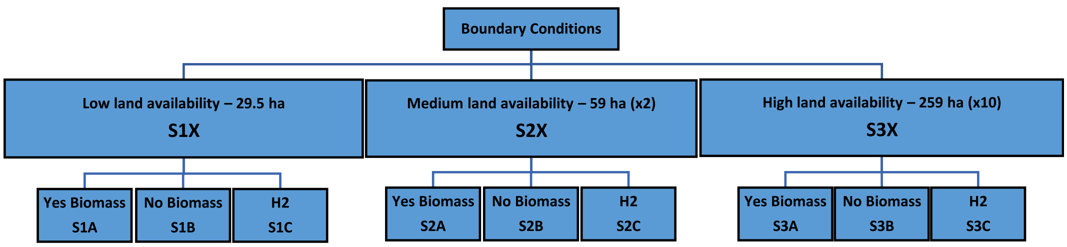

Fig. 6. Simulation scenarios map.

specifically wind, solar photovoltaic, and concentrating solar power.

For each of the three macro-categories, three sub-categories were further defined. Sub-category A sees a constant biomass supply chain as a viable option in the Sicily region, and therefore involves all technologies, including biomass boilers and biomass fired ORC. Sub-category B eliminates this assumption and cuts out the biomass technologies. Sub-category C was modeled in order to investigate a hydrogen-based optimization, by setting the upper boundaries of all non-hydrogen-related thermal technologies to zero.

The three different land areas, available for the installation of renewable energy technologies, are based starting with the land area suggested by the refinery. This suggested area of 29.5 ha, which was dedicated to the first macro category “S1 scenarios”, was then doubled (59ha) to obtain the second macro-category “S2 scenarios”, and finally multiplied by ten (295ha) to generate the third macro-category “S3 scenarios”.

In Fig. 6 the whole range of described scenarios is reported to highlight the distinction, while Fig. 7 provides a geospatial comparison among the three land areas.

On the basis of the available land areas, the potentialities for the installation of a wind park, a solar photovoltaic park and a concentrating solar thermal park were analyzed.

Concerning the wind park, in order to minimize wake effects, the turbines must be places roughly 5 times their diameter [46] from one another. S1 sees the installation of two 3.45 MW turbines with a rotor diameter of 136 m, yielding a total capacity of 6.9 MW. In S2 the total number of installable turbines is 4, for a total maximum capacity of 13.8 MW. In S3 16 turbines can be installed for a maximum capacity of 55.2 MW.

Concerning the solar photovoltaic (PV), it was first necessary to determine nominal power per unit of area. This was achieved by considering the spacing distance between the panels to avoid mutual shading as a function of the latitude (37.2 N). The power density of the PV park is determined to be 128.97 W/m^2. Therefore, the maximum capacities installable in the three different scenarios are 38.05 MW, 76.1 MW, and 380.5 MW.

Concerning CSP, the procedure aims to determine the potential annual thermal energy production from the available land area. The

Fig. 7. Light blue: land areas suggested as available by the refinery for the installation of renewable energy technology (S1 scenarios). Red: land area with twice the extension as the first (S2 scenarios). Dark blue: land area with ten times the extension of the first (S3 scenarios). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

thermal energy produced using a Linear Fresnel Reflector (LFR) in this geographical location is 661 kWh/year/m^2. According to [47], LFRs present a land use of 66% (to avoid mutual shading). Therefore, the land area actually required for the production of the above-mentioned 661 kWh/year is 1.52 times the unitary square meter. The total thermal energy that can be produced by LFR in the three different land area availability scenarios is 128.29 GWh/year, 256.57 GWh/year and 1.28 TWh/year, A further constraint regarding the two solar technologies (PV and LFR) is that their implementation cannot happen simultaneously. For any of the given available land areas, the sum of the areas occupied by PV and LFR cannot exceed the total available area.

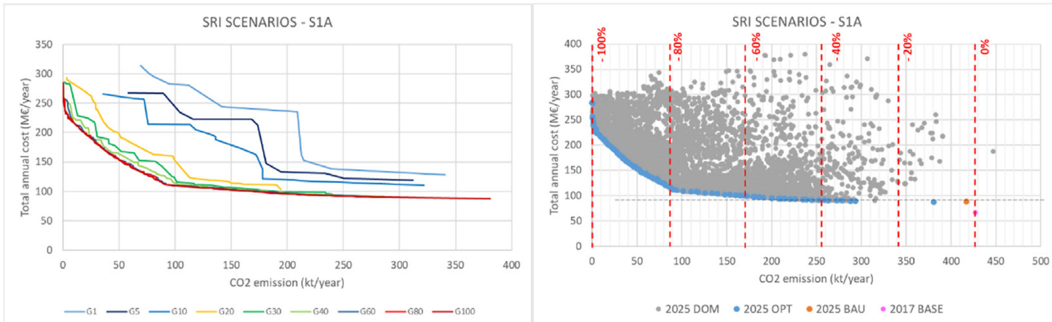

Fig. 8. (Left) Pareto front progression through the 100 generations. (Right) Final Pareto front of the 100 optimized solutions reported in blue. Reported in gray are all the dominated solutions (9900). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

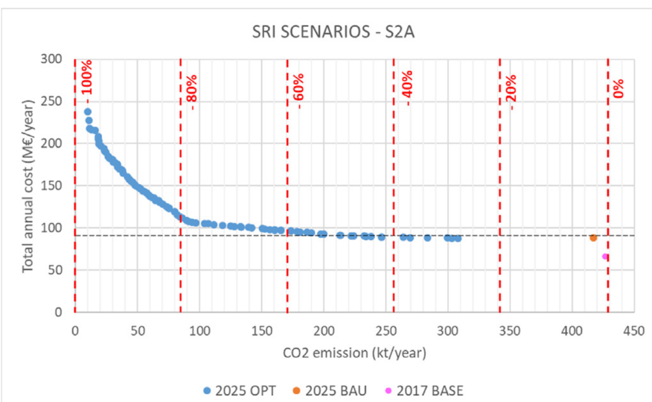

Fig. 9. Pareto front of optimal solutions of Scenario S2A.

3. Results

This section firstly presents the results in terms of annual costs and emissions obtained from the EnergyPLAN simulation of the Baseline 2017 and BAU 2025 models. The first provides annual costs and emissions of the reference year and the second the annual costs and emissions of 2025 if no sustainable interventions are made. In the second part of this section, the results of the EnergyPLAN + MOEA are reported, also highlighting the algorithm's convergence and the total simulation scenarios (Fig. 8). Focus is placed on scenario S2A by presenting the Pareto front of optimized scenarios (Fig. 9) and the combination of sustainable energy technologies for each of the energy sectors (Fig. 10 and Fig. 11). Finally, a direct comparison between the Pareto fronts of all 9 simulation scenarios is reported aggregated by land area availability and resource availability (Fig. 12 and Fig. 13).

3.1. EnergyPLAN baseline 2017

The outputs of the EnergyPLAN Baseline 2017 model are represented by annual costs and CO_2 emissions. The CO_2 emissions due to the combustion of 1,833 GWh of natural gas amount to 370 kt. The CO_2 emissions associated with the combustion of diesel and petrol by the refinery car fleet amount to 0.18 kt. The total electricity demand 2017 was 376 GWh. Of this, 311 GWh was produced through CHP (GTG-501) and 65 GWh was imported from the national electricity grid. The CO_2 emissions associated to the use of grid electricity may be assessed using the following equation:

$$CO_{2,imp} = \frac{E_{imp}}{\eta_{gen.2017}} (\%Coal \cdot e_{Coal} + \%Oil \cdot e_{Oil} + \%Gas \cdot e_{Gas})$$

Where E_{imp} is the imported electrical energy, $\eta_{gen.2017}$ is the national grid generation efficiency, $\%Coal$, $\%Oil$ and $\%Gas$ are the percentages of the fuels contributing to the energy mix of 2017 (as reported in Table 3), and e_{Coal}, e_{Oil} and e_{Gas} their respective emissions factors [48].

In addition to the emissions attributable to the national electricity grid, the CO_2 emissions of the SMR hydrogen production may be calculated as follows:

$$CO_{2,SMR} = \frac{H_{2,imp}}{0.69} \cdot e_{Gas}$$

The total imported hydrogen in 2017 was 124 GWh, and the efficiency attributable to (SMR) and compression was, in 2017, 69% ([49,50]). By dividing the total hydrogen import ($H_{2,imp}$) and the

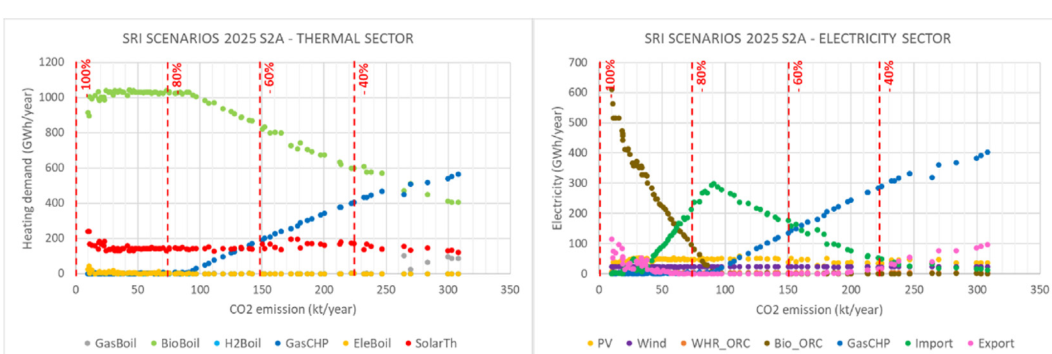

Fig. 10. Scenario S2A thermal sector (left) and electricity sector (right) annual productions per source. Decarbonization increases from right to left.

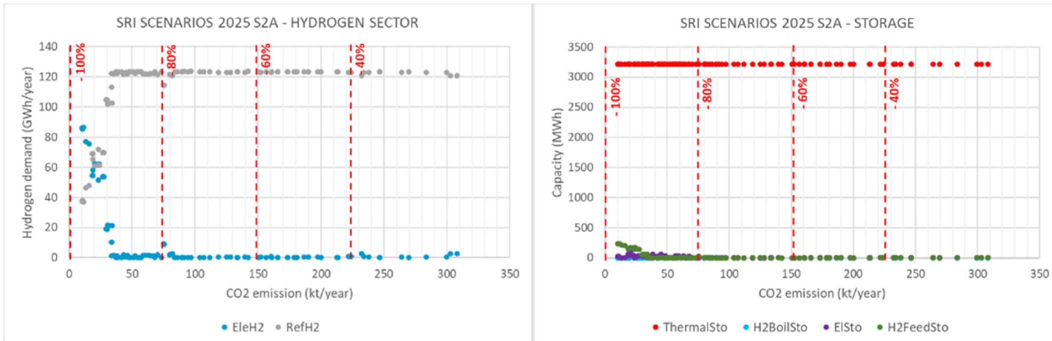

Fig. 11. Scenario S2A feedstock hydrogen sector (left) and energy storage sector (right) annual productions and capacities per source. Decarbonization increases from right to left.

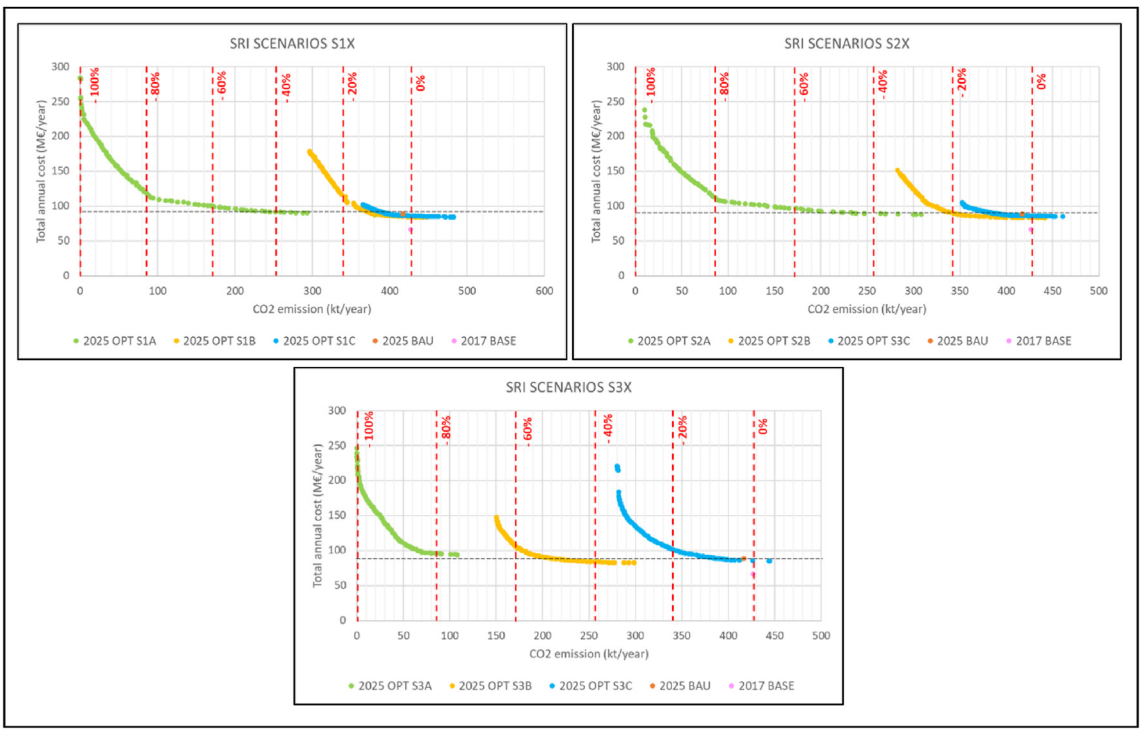

Fig. 12. Pareto front comparison by land availability. (Top left) low land availability (29.5 ha) with varying resources. (Top right) medium land availability (59 ha) with varying resources. (Bottom) high land availability (259 ha) with varying resources.

SMR efficiency, the total amount of natural gas used in SMR was obtained, value which was then multiplied by the emission factor of natural gas (e_{Gas}). The total CO_2 emissions attributable to imported hydrogen were, in 2017, 36 kt.

By adding all the individual CO_2 emissions together, the total CO_2 emissions modeled for the Baseline 2017 were 427 kt (Table 6).

As for the total annual costs, the total amount spent on natural gas was 45,553 k€, while 2,687 k€ was spent for the import of electricity. The excess electricity (0.36 GWh) was exported, gaining 13 k€. The costs attributable to CO_2 emissions, with a CO_2 price of 5.8 €/ton, were 2,148 k€. Concerning the electricity import, EnergyPLAN only accounted for the national electricity price (PUN), therefore the transmission and distribution price was added through post-processing (obtaining 8,170 k€). Bearing in mind that the imported hydrogen amounts to 124 GWh, the total amount spent on hydrogen in 2017 was 6,146 k€. In conclusion, the total annual expense of the Baseline 2017 was 66,525 k€ (Table 6).

3.2. EnergyPLAN business-as-usual 2025

The same considerations are brought forward for the EnergyPLAN BAU 2025 model. However, the CO_2 emissions show a lower value for the same energy demand. The reason being that in 2025 the energy mix of the national electricity grid will present a lesser portion of energy coming from high-emitting sources. The CO_2 emissions attributable to the import of electric energy pass from the 2017 value of 20 kt to the 2025 value of 12 kt. To a lesser extent, the improved efficiency of vehicles also lowers the total annual CO_2 emissions, passing from 0.18 kt in 2017 to 0.16 kt in 2025. Improved SMR and compression efficiency (72% [49,50]) of 2025 allow to lower the CO_2 emissions attributable to hydrogen import from 36 kt of 2017 to 35 kt in 2025. The total CO_2 emissions of the BAU model therefore are lower than the Baseline, passing from 427 kt to 417 kt (Table 6).

As for the costs, the total spent on the import of natural gas in 2025 would be 48,820 k€. This increase is due to the increase in the

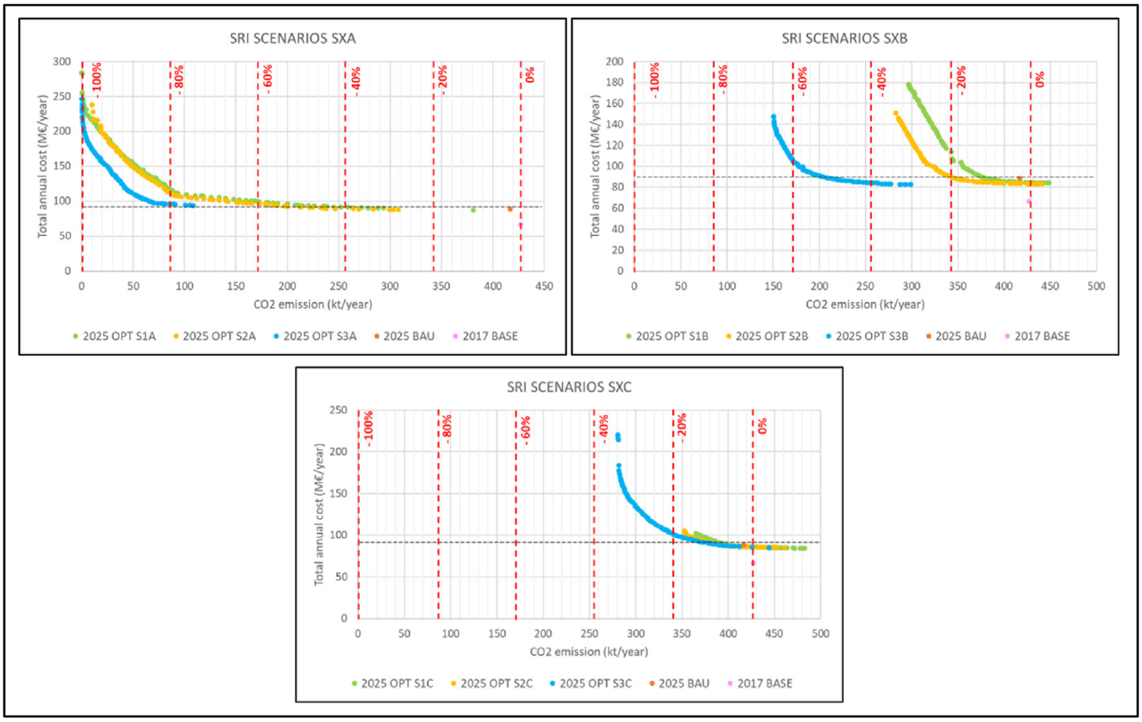

Fig. 13. Pareto front comparison by resource availability. (Top left) Assumption of presence of a biomass supply chain with varying land availability. (Top right) Exclusion of a biomass supply chain with varying land availability. (Bottom) Hydrogen based scenarios with varying land availability.

Table 6
Total annual CO_2 emissions and costs of the implemented import only model for the Baseline 2017 and the BAU 2025.

	Annual CO_2 emissions	Annual costs
	[ktCO$_2$/year]	**[K€/year]**
2017 Baseline	427	66,525
2025 BAU	417	88,604

price per MWh of natural gas from 24.9 €/MWh in 2017 to 26.6 €/MWh in 2025. The total amount spent on petrol and diesel for the refinery car fleet remains roughly the same as the increase in fuel price is balanced by the increase of vehicle efficiency. The most remarkable difference lies in the amount spent on CO_2 emissions. The expense forecasted for 2025 is 20,365 k€. This is due to the sharp rise of CO_2 price from 5.8 €/ton in 2017 to over 55 €/ton in 2025. The cost of hydrogen imported from outside the refinery increases by 20% due to the increase of the natural gas price and of cost of CO_2, passing from 6,146 k€ in 2017 to 7,562 k€ in 2025.

The total cost associated with the BAU 2025 model is 88,604 k€ (Table 6).

3.3. *Energy PLAN + MOEA sustainability vision 2025: optimized scenarios*

Reported in Fig. 8 (left) is the progression of the S1 Pareto front towards convergence to the optimal solution set during the 100 generations (G1 − G100). In the final generation there is a set of 100 dominant solutions (Pareto front) and roughly 10,000 (minus 100) dominated solutions. This is highlighted in Fig. 8 (right).

It was useful to superimpose the Baseline 2017 as well as the BAU 2025 scenarios on the same plot. This allows to visually grasp the difference in yearly costs and CO_2 emissions between these two and the Pareto front optimal solutions. The horizontal dashed line in Fig. 8 (right) helps to compare the yearly expenses of the BAU 2025 scenario with those of the decarbonized scenarios, highlighting the presence of several decarbonized scenarios with similar annual expenses but far lower CO_2 emissions.

Among the nine categories of scenarios, as a representative example S2A is described in detail. This is the first of the increased land area availability scenarios, with an area of 59 ha for the installation of wind power, concentrating solar thermal, and solar photovoltaic. Moreover, this scenario sees a constant biomass supply chain as a viable option in the Sicily region, and therefore includes biomass boilers and biomass ORC. The Pareto front in Fig. 9 shows how with annual expenses comparable to those of the BAU 2025 decarbonization of up to −80% is possible.

For each scenario a technological breakdown can be done for each refinery energy sector. The thermal sector is dominated by the key decarbonization role of biomass boilers in replacing the natural gas boilers and CHP (Fig. 10 (left)). Moreover, concentrating solar thermal is largely introduced in all scenarios, sharing the available area with the PV. The gas CHP phase out is also reflected in the electricity sector (Fig. 10 (right)). As the CHP electricity production decreases the initial export lowers. When this reaches zero, the import from the national electricity grid grows. The electrical import shows a maximum value where the self-produced electrical energy through biomass ORC begins. Indeed, the decarbonization capacity linked to the national electricity mix runs out towards the −80% target and it is necessary to resort to the more expensive, but completely renewable, biomass ORC technology.

Feedstock hydrogen is suggested to be imported from outside the refinery (produced from SMR) (Fig. 11 (left)), with the exception of highly decarbonized scenarios. Indeed, only in exceeding the target of −90% it is suggested to resort to the expensive production of hydrogen by electrolysis. Here, the increase of electrolytic hydrogen justifies the continuous rise of the biomass fired ORC to produce the required green electrical production. Unfortunately, the small area available, in relation to the high energy demand of the refinery, does not allow to rely on large quantities of electricity from wind and PV to produce green hydrogen. As for the energy storage sector (Fig. 11 (right)), thermal energy storage is combined with the concentrating solar thermal and therefore relevant in all scenarios, feedstock hydrogen storage is observed only in highly decarbonized scenarios, while electrical storage (batteries) and storage for hydrogen blending in boilers are never relevant.

Finally, the results of the transport sector are not reported here because they have not given significant indications, in fact the energy demand of this sector is so irrelevant that it does not influence the overall choices of EnergyPLAN + MOEA.

With reference to the deeply decarbonized scenarios characterized by large capacities of biomass boilers and biomass ORC, it is of relevance to put their biomass demand in perspective with the potential supply of the Sicilian region. Among the SXA scenarios, S1A presents the highest share of biomass between 80% and 100% CO_2 emissions reduction, in both the thermal and electrical sector. The annual thermal and electrical energy provided by biomass boiler and biomass ORC reach a maximum of 1169 and 772 GWh/year, respectively. These values are translated into their respective biomass input through the thermal efficiency of the biomass boiler (84% [45]) and the electrical efficiency of the biomass ORC (16% [45,51]), an amount to 1,392 and 4,825 GWh/year, respectively.

Assuming a residue-based supply of biomass (as opposed to dedicated bioenergy crops, which may come into conflict with food agriculture), a census carried out by the public company Ricerca sul Sistema Energetico of the Italian national energy biomass potential [52] reports that Sicily can exploit up to 7.60 TWh/year of solid biomass and 1.15/year TWh of biogas. The solid biomass is composed by 43% straw, 40% prunings, 16% olive oil and wine production residues, and 2% forestry residues. On the other hand, biogas is produced from 56% urban organic waste, 43% wastewater, and 1% slaughterhouse waste. This data highlights how the overall maximum biomass demand in scenario S1A of 6.22 TWh/year could potentially be covered regionally.

3.3.1. Comparison among the nine categories of scenarios

Given the vast number of simulations, it is useful to directly compare the Pareto fronts of the nine categories of scenarios among them. The approach taken is that of comparing the Pareto front solutions firstly by land availability (S1, S2, S3) in Fig. 12, and secondly by resource availability (A, B, C) in Fig. 13. The conclusion drawn is that completely decarbonized scenarios are only reported when biomass-fired technologies are available (A). If the biomass supply chain assumption is removed, increasing the land area availability helps the decarbonization, but however the benefit obtained is not proportional to the increase of land.

4. Conclusions

With this study, a sustainability vision for the SRI refinery was conducted on the basis of the innovative EnergyPLAN + MOEA methodology, investigating the potential of multiple decarbonization technologies, considering three different land availabilities. Sonatrach Raffineria Italiana (SRI) – Raffineria di Augusta is willing to refurbish its energy system in order to cut down costly CO_2 emissions.

This study can be divided into three parts. The first part was dedicated to data collection. It was necessary to extrapolate from the refinery provided data the portion of the overall data, useful to the scope of the assessment. It was discovered how most of the refinery's energy demand is satisfied by refinery fuel gas. This posed an important limit to the analysis, as refinery fuel gas is a by-product of oil refining and is directly tied to the refinery's productive activity. Since it was expressly demanded by the refinery that their production has to remain independent of the decarbonization strategy, all refinery gas was excluded from the study. This led to the definition of an "import only" model, comprising only the imported natural gas, electricity, SMR hydrogen, and petrol/diesel for vehicles.

The second part in the methodology consisted in recreating the "import only" model of a reference year in EnergyPLAN (Baseline 2017). The validation of this model occurred by comparing the outputs of the software with actual values of annual costs and CO_2 emissions provided by the refinery. A second model was created to envision a 2025 scenario in which no interventions in the SRI energy system will be made. This business-as-usual 2025 scenario served as a term of comparison with the decarbonized scenarios. The third step of the methodology consisted in implementing the EnergyPLAN + MOEA tool. Multiple 2025 scenarios were run in order to ensure a broad spectrum of solutions. Three macro-categories were identified based on increasing land area availability for the installation of renewable technologies (S1X, S2X, S3X). Each category was then further divided in three different sub-categories. This allowed to simulate how an optimal energy system would look like, with (SXA) and without a biomass supply chain in the region (SXB and SXC), and with hydrogen blending in gas boilers as the sole renewable solution in the thermal sector (SXC).

By analyzing the results of the different scenarios and comparing them with one another, it becomes clear that completely decarbonized scenarios are only witnessed when a programmable and steady source of biomass can be exploited (SXA). However, only if the biomass is used as fuel in steam generators and furnaces the decarbonized solutions are also economically attractive, as opposed to the costlier biomass ORC implementation. In all other cases (SXB and SXC), the proposed alternative renewable sources of heat and electricity, *i.e.* wind power, PV and concentrating solar thermal, are unable to have such substantial impact on the CO_2 emissions. Moreover, the simulations were run for the "import only" model, while this model includes 100% of the hydrogen demand and 86% of the electricity demand, it only regards for 17% of the refinery furnaces' process heat and 25% of the refinery steam generation, the remaining is satisfied by refinery fuel gas, a by-product of the refining process, which is responsible for most of the refinery's CO_2 emissions. Overall, the SRI decarbonization will be key to address lower free emission allowances and higher CO_2 costs planned by the 2030 and 2050 European climate and energy plans.

Declaration of competing interest

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

Appendix A

Recalling the diversification of the simulation scenarios reported in section 2.6, and with the aid of the scenario map in Fig. 6, each scenario can be analyzed further in terms of decision variables and boundaries. The scenario chart in Table 7 displays the upper boundaries of the scenario-dependent decision variables.

Table 7
Scenario chart. Scenario-dependent upper boundaries of the decision variable search space are defined based on the land and resource availability assumptions. Boundaries set to null values represent the exclusion of the technology from the scenario.

Technology	Unit	S1A	S1B	S1C	S2A	S2B	S2C	S3A	S3B	S3C
PV	MW	38.35	38.35	38.35	76.7	76.7	76.7	383.5	383.5	383.5
Wind	MW	6.9	6.9	6.9	13.8	13.8	13.8	31.05	31.05	31.05
Biomass St. Gen./Furnaces	GWh/year	1177.06	0	0	1177.06	0	0	1177.06	0	0
Biomass ORC	MW	101.38	0	0	101.38	0	0	101.38	0	0
Electric St. Gen./Furnaces	GWh/year	1177.06	1177.06	0	1177.06	1177.06	0	1177.06	1177.06	0
Solar thermal	GWh/year	128.6	128.6	0	257.2	257.2	0	1286	1286	0
Battery	MWh	362	362	362	724	724	724	3316.4	3316.4	3316.4

With Table 8 a complete overview of the decision variables of the EnergyPLAN + MOEA simulations is presented.

Table 8
Upper and lower boundaries of all the decision variables implemented in this assessment. Scenario-dependent boundaries are to be found in Table 7. EP = EnergyPLAN.

2025			
Technology	Min	Max	Unit
Electric Energy Production			
Photovoltaic.	0	See scenario chart.	kW
Wind.	0	See scenario chart.	kW
Waste heat ORC.	0	406	kW
Biomass ORC.	0	See scenario chart.	kW
National electric grid.	Calc. by EP, no grid constr.		GWh/year
Cogeneration			
Natural gas CHP.	0	1177.06	GWh/year
Thermal Energy Production			
Natural gas steam generators/furnaces.	0	1177.06	GWh/year
Hydrogen steam generators/furnaces.	0	1177.06	GWh/year
Biomass steam generators/furnaces.	0	See scenario chart.	GWh/year
Electric steam generators/furnaces.	0	See scenario chart.	GWh/year
Concentrating solar thermal.	0	See scenario chart.	GWh/year
Hydrogen			
Electrolytic feedstock H_2.	0	123.62	GWh/year
Steam methane reforming feedstock H_2.	0	123.62	GWh/year
Electrolytic production for H_2 steam generators/furnaces.	Calc. by EP as min cap. needed		kW
Electrolytic production for feedstock H_2	Calc. by EP as min cap. needed		kW
Transportation			
Petrol vehicles.	0	1152001	km/year
Diesel vehicles.	0	1152001	km/year
Battery electric vehicles.	0	1152001	km/year
Storage			
Electric storage - Batteries.	0	See scenario chart.	MWh
Thermal energy storage for concentrating solar thermal.	Cons. cap. of 1 day of av. heat dem.		MWh
H_2 gas storage for H_2 steam generators/furnaces.	Cons. cap. of 1 day of av. H2 dem.		MWh
H_2 gas storage for H_2 as feedstock.	Cons. cap. of 1 day of av. H2 dem.		MWh

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2022.100076.

References

[1] United Nations. Kyoto Protocol to the united nations framework convention on climate change. 1998.
[2] United Nations. Framework convention for climate change. Paris Agreement 2021 [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
[3] UNFCCC. Organization of work, including for the sessions of the subsidiary bodies. 2021. Glasgow.
[4] Our world in data based on global carbon project; BP; maddison; UNWPP, "CO2 emissions [Online]. Available: https://ourworldindata.org/co2-emissions. [Accessed March 2021].
[5] Masnadi MS, Jing L, Monfort J-C, Brandt AR, El-Houjeiri HM, Gordon D, Bergerson JA. Carbon intensity of global crude oil refining and mitigation potential. Nat Clim Change 2020;10:256–532.
[6] Byrum Z, Pilorgé H, Wilcox J. Technological pathways for decarbonizing petroleum refining. 21 October 2021. https://doi.org/10.46830/wriwp.21.00004 [Online]. Available:.
[7] Gudde N, Larivé J-F, Yugo M. CO2 reduction technologies. Opportunities within the EU Refining System (2030/2050). Brussels: Concawe Special Task Force; 2019.
[8] Studies TO IfE. Decarbonization pathways for oil and gas [Online]. Available: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf; March 2020.
[9] Rissman J, Bataille C, Masanet E, Aden N, Morrow III WR, Zhou N, Elliott N, Dell R, Heeren N, Huckenstein B, Cresko J, Miller SA, Roy J, Fennell P, Cremmins B, Koch Blank T, Hone D, Williams ED, de la Rue du Chan S, Sisson B, Williams M, Katzenberger J, Burtraw D, Sethi G, Ping H, Danielson D, Lu H, Lorber T, Dinkel J, Helseth J. Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Appl Energy 2020;266:114848.
[10] Berghout N, Meerman H, van den Broek M, Faaij A. Assessing deployment pathways for greenhouse gas emissions reductions in an industrial plant – a case study for a complex oil refinery. Appl Energy 15 February 2019;236:354–78.
[11] Absi Halabi M, Al-Qattan A, Al-Otaibi A. Application of solar energy in the oil industry—current status and future prospects. Renew Sustain Energy Rev March 2015;43:296–314.
[12] M. &. Co. The Future is now: how oil and gas companies can decarbonize [Online]. Available: https://www.mckinsey.com/∼/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/The%20future%20is%20now%20How%20oil%20and%20gas%20companies%20can%20decarbonize/The-future-is-now-How-oil-and-gas-companies-can-decarbonize.pdf; January

2020.
[13] Manna J, Jha P, Sarkhel R, Banarjee C, Tripathi A, Nouni M. Opportunities for green hydrogen production in petroleum refining and ammonia synthesis industries in India. Int J Hydrogen Energy 8 November 2021;46(77):38212–31.
[14] Nurdiawati A, Urban F. Decarbonising the refinery sector: a socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. Energy Res Social Sci February 2022;84.
[15] Li J, Zhao H. Multi-objective optimization and performance assessments of an integrated energy system based on fuel, wind and solar energies. Entropy 2021;23(4).
[16] Hori K, Kim J, Kawase R, Kimuar M, Matsui T, Machimura T. Local energy system design support using a renewable energy mix multi-objective optimization model and a co-creative optimization process. Renew Energy 2020;156:1278–91.
[17] Al Hasibi RA. Multi-objective analysis of sustainable generation expansion planning based on renewable energy potential: a case study of Bali Province of Indonesia. Int. J. Sustain. Plan. Manage. 2021;31:189–210.
[18] Wang Y, Huang F, Tao S, Ma Y, Yuze M, Liu L, Dong F. Multi-objective planning of regional integrated energy system aiming at exergy efficiency and economy Yongli. Appl. Energy j. 2022;306(PB):118120.
[19] Alnifro M, Taqvi S, Ahmad M, Bensaida K, Elkamel A. Optimal renewable energy integration into refinery with CO2 emissions consideration: an economic feasibility study. In: IOP conference series: earth and environmental science. Rome: Italy; 2017.
[20] Taqvi S, Almansoori A, Elkamel A. Optimal renewable energy integration into the process industry using multi-energy hub approach with economic and environmental considerations: refinery-wide case study. Comput Chem Eng August 2021;151:107345.
[21] Mahbub S, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51.
[22] Mahbub S, Viesi D, Crema L. Designing optimized energy scenarios for an Italian Alpine valley: the case of Giudicarie Esteriori. Energy 2016;116:236–49.
[23] Mahbub S, Viesi D, Crema L. An innovative multi-objective optimization approach for long-term energy planning. Appl Energy 2017;208:1487–504.
[24] Viesi D, Crema L, Mahbub S, Verones S, Brunelli R, Baggio P, Fauri M, Prada A, Bello A, Nodari B, Silvestri S, Tomasi L. Integrated and dynamic energy modelling of a regional system: a cost-optimized approach in the deep decarbonisation of the Province of Trento (Italy). Energy 2020;209:118378.
[25] Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. Appl Energy 1 February 2019;235:356–68.
[26] Prina MG, Cozzini M, Garegnani G, Manzolini G, Moser D, Filippi Oberegger U, Pernetti R, Vaccaro R, Sparber W. Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model. Energy 15 April 2018;149:213–21.
[27] Prina MG, Moser D, Vaccaro R, Sparber W. EPLANopt optimization model based on EnergyPLAN applied at regional level: the future competition on excess electricity production from renewables. Int. J. Sustain. Energy Plann. Manage. March 2020;27:35–50.
[28] 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 1 April 2020;196:117062.
[29] Bellocchi S, De Iulio R, Guidi G, Manno M, Nastasi B, Noussan M, Prina M, Roberto R. Analysis of smart energy system approach in local alpine regions - a case study in Northern Italy. Energy 1 July 2020;202:117748.
[30] Østergaard AP. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33.
[31] EnergyPLAN, "Advanced energy system analysis computer model," Aalborg Univ., [Online]. Available: https://www.energyplan.eu/.
[32] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN e Advanced analysis of smart energy systems. Smart Energy February 2021;1.
[33] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, Thellufsen JZ, Sorknæs P. Energy storage and smart energy systems. Int. J. Sustain. Energy Plann. Manage. 2016;11:3–14.
[34] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 15 October 2017;137:556–65.
[35] Sorknæs P, Lund H, Skov I, Djørup S, Skytte K, Morthorst P, Fausto F. Smart Energy Markets - future electricity, gas and heating markets. Renew Sustain Energy Rev March 2020;119:109655.
[36] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, Karnøe P. Simulation versus optimisation: theoretical positions in energy system modelling. Energies 23 June 2017;10(7).
[37] Luo S, Hu W, Liu W, Xu X, Huang Q, Chen Z, Lund H. Transition pathways towards a deep decarbonization energy system—a case study in Sichuan, China. In: Contents lists available at ScienceDirect Applied. 302; 2021. p. 117507.
[38] Unione Petrolifera (up), ENEA, "Linea Guida per la redazione della Diagnosi Energetica nel settore petrolifero".
[39] Gaggiotti IM. Rapporto di Diagnosi Energetica ai sensi del D.Lgs. 102/2014. 2018.
[40] [Online], https://www.mercatoelettrico.org/It/Default.aspx.
[41] [Online], http://www.rse-web.it/home.page.
[42] [Online], https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union.
[43] Ministero dello sviluppo economico. Piano Nazionale Integrato per l'Energia e il Clima; 2020.
[44] GSE [Online], www.gse.it/dati-e-scenari/monitoraggio-fer/monitoraggio-nazionale/settore-elettrico; February 2021.
[45] European Commission. Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU. JRC; 2017.
[46] Battisti L. Gli impianti motori eolici - seconda edizione. Lorenzo Battisti Editore; 2019.
[47] Bolognese M, Crema L, Patticò L, Viesi D, Bartali R. Solar thermal technologies for low-carbon industrial processes: dynamic modelling, techno-economic analysis and environmental impact. Multidiscip. Dig. Publish. Inst. Proceed.(MDPI) 2020;58(1):14.
[48] Covenant of Mayors. The covenant of mayors for climate and energy reporting guidelines. 2016.
[49] Econometrics Cambridge. Fuelling's Italy's Future: how the transition to lowcarbon mobility strengthens the economy. 2018.
[50] Viesi D, Crema L, Testi M. The Italian hydrogen mobility scenario implementing the European directive on alternative fuels infrastructure (DAFI 2014/94/EU). Int J Hydrogen Energy 2017;42:27345–73.
[51] Duvia A, Guercio A, Rossi C. Technical aspects of Biomass fuelled CHP plants based on ORC turbogenerators feeding existing district heating networks. In: Proc. 17th eur. Biomass conf., hamburg; 2009.
[52] Motola V, Colonna N, Alfano V, Gaeta M, Sasso S, De Luca V, De Angelis C, Soda A, Braccio G. Censimento potenziale energetico biomasse, metodo indagine, atlante Biomasse. RSE; 2009.