Moving the system boundaries in decarbonization of large islands

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Abstract

During the last few years, the majority of the EU Governments are implementing suitable energy policies, promoting a transition toward full decarbonized sustainable energy systems by 2050. This paper focuses on creating comprehensive decarbonization scenarios for the island systems, using EnergyPLAN software. The island of Sardinia, Italy, was selected as a case study. The presented method uses scenario approach and seeks to push the boundary of the island energy system and use the locally available resources to partially supply the maritime transport connecting the island to the mainland. The reference model was validated using the data provided by EDGAR and IEA for 2017. The Business as Usual Scenario and High Renewable Scenario by 2030 and 2050 were modelled. The latter considers the conversion of the Sardinia energy system into a smart, highly efficient and integrated system. For the power system, improvements are made by the installation of small decentralized renewable systems, mainly including photovoltaic and wind technologies, and increase of storage technologies use. Thermal demand is reduced by building energy refurbishment actions, including the envelope insulation and use of heat pumps. For the transport sector, raise of the share of electrical vehicles is expected, as well as the possibility to introduce biofuels in both maritime and road transport sectors. Results clearly show that carbon neutrality by 2050 is a reasonable target in different decarbonization scenarios. The study also provides useful suggestions to be implemented in order to achieve this goal.

Keywords: Sustainable islands, smart islands, RES integration, decarbonization.

1. Introduction

Energy security of supply is a crucial factor for the progress of our society. Energy is used for the production of the main goods and maintaining the standard of living. The intensive exploitation of

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fossil energy sources has made available an unprecedented amount of goods and services and allowed for economic, cultural and environmental development. The incessant increasing of the global energy consumption, at about 2.3% per year [1], and the reduced availability, as well as the environmental externalities of conventional energy sources, pose economic, political and environmental problems. Decision-makers must respond adequately to these circumstances. Therefore, renewable energy sources (RES) play a key role in energy transition. The transition from a fossil fuel-based economy to renewables mainly addresses the issue of the climate change, with the primary goal of reducing the amount of Green House Gases (GHG) emissions released per year in the atmosphere, promoting a more efficient and rational use the available resources.

This study is based upon a regulatory framework adopted at the twenty-first Conference Of Parties held in Paris in 2015 [2], aiming to limit the phenomenon of global warming below 2°C compared to pre-industrial levels. With this in mind, several EU regulations have followed during the past few years, updating the Climate Energy Package 2020, known as Directive 20/20/20 [3], (in which the EU undertakes to reduce CO_2 emissions by 20% compared to 1990, to increase the share of energy produced from renewable sources by 20% and to cut the annual share of energy consumption by 20%) with the three new and more ambitious targets to be reached by 2030: 40% greenhouse gas emissions reduction below 1990 levels, at least a 32% share for renewable energy and at least a 32.5% improvement in energy efficiency [4]. The Covenant of Mayors [5] is the bridge between European and local authorities in terms of energy planning and implementation of the interventions. As for the year 2050, the goal set by EU in the Energy Roadmap is the complete decarbonization of the European economy, reaching a zero net emission balance [6]. The achievement of this goal implies by 2050 the almost complete decarbonization of power sector [7], necessarily involving a process of raising efficiency and innovation that could simultaneously strengthen security of supply and competitiveness in Europe. In order to increase the use of RES and solve the carbon dioxide problem, a radical change in the energy system is required [8]. Other clean energy measures could include the electrification of various sectors, use of hydrogen produced from RES, product substitution, sustainable and green bio-based products, CO_2 capture and storage technologies [9]. To address the different regulations, each country has implemented its own energy policies without the coordination with other nations. The measures facilitate the proliferation of RES technologies. The recent large utilization of RES technologies dramatically affects the management of the electrical networks, due to the peak surplus of energy, which cannot be handled without a suitable infrastructure. In order to address these issues, the adoption of an integrated planning approach has become fundamental on different scales, whether it is a nation or a region. The energy planning is clearly the method towards the development of a smart energy system utilizing the synergies in the system, using different alternative technologies to maximize efficiency and reduce costs [10], especially when the system has to be converted to a 100% renewable energy system. Different approaches, without solid base in energy planning, could lead to promoting inappropriate solutions or supporting only some of the technologies, risking the surplus energy production [11].

2. Literature review

2.1. Energy planning of small island energy systems

The energy planning approach has been implemented in several literature works [12-14]. In this framework, special attention has been paid to the issue of the stability and flexibility of the network in systems strongly depending on RES, such as smart island systems. The energy planning of self-sufficient isolated systems, such as islands, is a challenging topic due to the limited availability of local energy sources. Small islands are interesting territories to experiment innovative solutions to reach energy sustainability [15]. A hybrid system, which includes solar photovoltaics (PV), wind turbines and battery was studied in [16] on a case of isolated islands, in terms of size of storage and its state of charge, systems net present cost, excess electricity generation, levelized cost of energy and the payback for the system. The research provided energy balance for the whole year and demonstrated that the system is viable, while pick pointing that battery cost, wind turbines cost, and electricity load are the most relevant for the systems cost. Ocon and Bertheau [17] reduced the reliance on diesel power plants in off-grid island areas by proposing solar photovoltaics-battery-diesel hybrid systems. The results of their research on the example of small island grids in Philippines show that such solutions reduce the system cost for 20%, with possible increase as the cost of PV and batteries decline. The benefits of the connection lines for resorts which aim to use microgrids are analysed in [18], with results showing the costs decrease of 43% in case the connection power line is constructed, enabling such resorts to use locally available renewable energy to participate in power markets. Furthermore, it seems obvious that islands need alternative green energy scenarios to balance their high dependence to fossil fuel imports for electricity generation [19]. In [20] authors studied configurations of energy system using HOMER software. Through scenarios that including hydrogen and batteries storage for small islands they demonstrated the decarbonization of electricity and road transport sectors in an environmentally sustainable way. Pfeifer et al. [21] presented a work for the implementation of zero emission ferry lines, for the connection and interconnection of the mainland with future 100% RES islands. The analysed scenarios include diesel, hydrogen and fully electricity fuelled ferries. The resulted operation costs of fully electricity fuelled ferries are the lowest ones. Calise et al. [22] proposed a detailed analysis of the possible decarbonization scenarios for Italy presenting different alternative pathways to reduce by at least 80% of GHG emissions by 2050, with respect to 1990. Solar and wind power, combined with biomass-fuelled CHP plants are expected to cover the future electricity demand. In transport sector, the use of synthetic fuels produced by electrolytic converters is expected to match the majority of the user energy demand. The main results are as follows: i) the share of RES by 2050 in electricity production is higher 90%, ii) a reduction by 60% in fossil fuel consumption; iii) a CO_2 emissions reduction of over 82% and over 85% with respect to 2014 and 1990 level, respectively. Alves et al. [23] considered the case study of two islands in the Azorre archipelago, the Pico and Faial Islands, to outline possible paths for 100% renewable energy systems. The stability issue and the mismatch between demand and supply are also discussed in this work. The assessment of the impact of the interconnection of two small islands in the path to 100% RES of the whole energy system is performed in EnergyPLAN. Results show that by considering the islands with independent power systems, Pico Island is able to achieve a RES share of 100%, but not Faial Island, that only reaches 70%. Conversely, the Islands interconnection allows one to achieve 100% renewable energy system in both Islands. A study conducted on the Croatian island of Korčula, in terms of energy planning is reported in reference [4]. This study finds its pivotal point in the implementation of the vehicle-to-grid concept for road transport but also ferry lines to and from the island. Concretely, smart charging vehicles and ferries are connected to the grid and allow charging and discharging of the batteries in order to reduce energy import and export while at the same time minimizing production from conventional power plants. The method proposed in reference [24] aims to show how the development of 100% renewable island energy systems can be reached by interconnections of a group of islands integrating the production from locally available RES. In this paper, Islands of Vis, Korcula, Lastovo and Mljet are investigated and the following energy actions for the year 2035 are considered. Electric vehicles are connected to the grid using the vehicle-to-grid concept and those vehicles can be considered as potential storage systems for the variable energy production. Different scenarios in terms of stationary batteries location are also taken into account, i.e. several smaller distributed batteries and one big central battery. The results show that by interconnection a high share, equal to 85%, of energy from RES in total final energy consumption is obtained, as well as a reduction in the total critical excess electricity production of all systems from 28 to 35% individually to 13%. The same approach is also addressed in reference [25] where a scenario of decarbonisation by 2050 for small islands and archipelagos of the Canary Islands is proposed. Integrating the different energy sectors and by a sea cable connections among all islands, they estimate a reduction in supply cost by 15%. Marczinkowski and Østergaard [26] investigated the possibility to increase the local use of renewable electricity for the islands Samsø and Orkney (Scotland) by two different energy planning approaches. In particular, they compared the use of Battery Energy Storage Systems (BESS) and the conversion of renewable electricity to heat, thus enabling the usage of Thermal Energy Storage (TES), using EnergyPLAN. The results of comparison show that BESS tend to address only the electricity sector, while combining electricity with heating through HP and TES, further possible enhancements in the transport sector by freeing biomass resources, with an overall reduction of the energy system costs, are obtained.

2.2. Optimization of the system's configuration and demand side management

Energy efficiency measures and measures aiming to implement demand side management are important steps in energy transition of small and large islands. Also, optimization approaches for finding the optimal configuration of the energy systems on islands were recently investigated in several papers. Important energy efficiency measures such as retrofit of lighting system and installation of smart lighting were studied in [27], showing that such measures have very short time of return of investment. Another hybrid system, including PV module, biogas generator, wind turbine and batteries was proposed by [28] as a solution for a remote island, Saint Martin in Bangladesh. The multi-objective optimization with sorting genetic algorithm was used to determine the size of components. The results were focused on the proof that such intelligent techniques give better results than using a single objective function. In [29] the Green Energy Island is defined as a system which supplies energy for heating, cooling and electricity. The authors proposed Hammersly sequence sampling to show how a lot of time can be saved in determining the results to multi-objective problem in finding the optimal system configuration. Important topic of demand side management, that can be used in city district, but also for large islands, was investigated in [30], considering prosumers, heat pumps and solar PV. Results proved the cost reduction and rise in self-sufficiency for the case of a district in La Graciosa Island. Wang et al. [31] addressed with the optimal planning of a 100% renewable energy island supply system, considering the integration of desalination units and concentrating solar power plants (CSP). To solve the typical issues of isolated islands, i.e. the environmental-unfriendly power supply and freshwater scarcity, authors propose the flexibility of CSP plants to guarantee a more stable production obtained by wind turbines (WTs). A thermal storage system is included with the aim to reduce the battery energy storage configuration for islands. To verify the effectiveness of the proposed scheme, Astypalaia island (Greece) is used in this case. Results suggest that for islands with short offshore distance and stable load, it is more profitable and reliable to use cable interconnection for water and power supply.

2.3. Biofuels production from local feedstock

The use of biogas obtained from the anaerobic digestion is also another energy attractive action significantly investigated in the literature to increase the renewable energy sources is [32]. The anaerobic digestion process can be performed using almost any kind of organic matter [33]. In an island context, biogas can be used for grid stabilization when high renewable, variable electricity is introduced in an energy system, such as solar and wind energy, as biogas can be easily stored or produced on-demand [34, 35]. An example of this approach is addressed by Suarez et al. [36] evaluating the biogas production from animal manure produced in different farms (poultry, sheep, swine, cows or goats) in the Canary Islands as additional energy source for producing heat and electricity. They calculated that with a total manure production of 495,622 t/year, the overall potential biogas production is about 27.1 Mm^3/year. The related potential GHG emissions savings due to the production of biogas from animal manure could reach yearly 55,745.1 tons of carbon dioxide equivalents, including both substitution of fossil fuels and appropriate management of animal manure. Another study [37] reviewed the potential of energy production from AD of the different biomass or wastes available in Mauritius island. Based on the review, the net energy available from AD of the various wastes/biomass studied is 4685 TJ/year, i.e. 12.6% of the final energy consumption of the island. Among the different substrates reviewed, authors determined that sugarcane field-based agricultural residues (3790 TJ/year), organic fraction of municipal solid wastes (462 TJ/year), and vinasse (268 TJ/year) are the feedstocks with the higher energy potential from large scale AD in Mauritius. In Europe, the main producers of biogas by anaerobic digestion are Germany, Italy and UK. Meyer et al. [38] investigated the potential substitution in the EU of natural gas with biogas produced from animal manure, straw and grass to be 9–16%. A general trend that has been adopted by many countries is to shift from fossil fuels towards renewables. This goal may be achieved by the conversion of biomass and waste materials to energy: for example, the production of bioethanol from lignocellulosic materials via the biochemical processes [39], or of biodiesel from residual vegetable oils [40]. In Italy, the biogas production including agricultural, agri-industrial and organic fraction of municipal solid waste has increased from 323.9 millions of tons in 2011 [41] up to 1570.8 millions of tons in 2016 [42]. Biomethane, obtained by the upgrading of biogas, can be used for transport or for injection in the natural gas grid, substituting fossil fuels. Note that in the current gas grid in Italy, a certain amount of natural gas already consists of biomethane obtained by anaerobic digestion.

2.4. Problem formulation and hypothesis

As far as Italy is concerned, the following energy planning tools are presently implemented: i) the Action Plan for Energy Efficiency (APEE) which provides detailed indications regarding the actions to be implemented to achieve the objectives of improving energy efficiency; ii) the National Action Plan (NAP) which provides detailed indications regarding the actions to be implemented to cover an amount of the total gross consumption with energy produced from RES. In order to achieve this goal, Italy promotes the burden sharing wherewith each Region and autonomous Province is assigned a different emission threshold to be achieved within the expected time, commensurate with the specificities of the Regions. This translates into the Regional Energy and Environmental Plan (REEP), drawn up each year by the Regions in order to analyse the system in its composition and outline a technical and practical line of action for the achievement of intermediate objectives. At the best of the authors' knowledge, the energy planning approach has been implemented for the first time in this paper for the case study of the autonomous Region of Sardinia (Centre of Italy), considered of particular interest for the isolated nature of the region as an island and specific size of the island, which is larger (with over 1 million inhabitants) than any island considered in the reviewed literature. The final goal of this paper is the development and modelling of future energy scenarios based on the concept of smart energy system characterized by a high percentage penetration of RES into the island system, the electrification of energy-consuming processes, the mutual connecting of the electricity, heat, transport and industry sectors, and the development of diversified and efficiency energy storage systems. This research hypothesises that it is possible to determine the locally optimal dynamics of energy transition for large islands using the scenario analysis approach that is elaborated in the method.

The article is structured as follows. Section 3 describes the method applied using the software EnergyPLAN. Section 4 outlines the case study in the reference year, 2017. Section 5 outlines the methods used to obtain data implemented for EnergyPLAN and their validation by comparing the model results with real and prediction data. Section 6 describes the future scenarios modelled. Section 7 reports on the results of the future scenarios and section 8 brings the conclusions of the study.

3. Method

In order to develop the models related to the considered energy scenarios, the EnergyPLAN software was used. EnergyPLAN was developed at the University of Aalborg, Denmark, and it has been continuously expanded since 1999; it represents an analysis tool of the energy system and it is analytically programmed to simulate the yearly working time of an energy system. EnergyPLAN is an analysis model of the input/output energy system in which the input defines the energy system in terms of demand, capacity and efficiency. Principal scheme of EnergyPLAN is given in Figure 1.

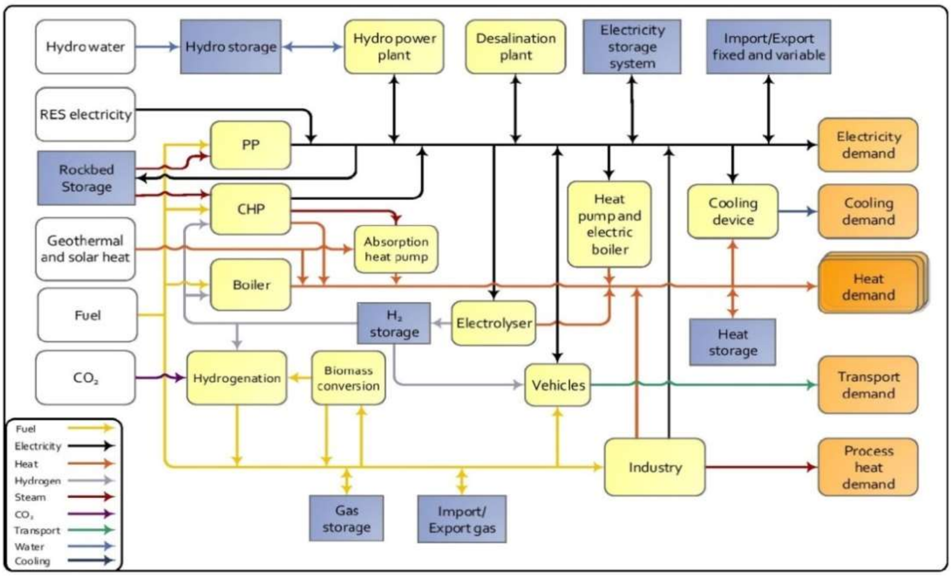

Figure 1 Schematic diagram of the EnergyPLAN model [20]

The output is the performance of the energy system in terms of CO_2 emissions, fuel consumption and amount of renewable energy included. Regarding the CO_2 emission factors, the software provides standardized coefficients for the different fuels, expressed in terms of kg of CO_2 emitted per GJ of fuel used. The coefficients refer to average values related to the European data. The values provided by the software were accepted as valid and realistic for the case study in question. In fact, the use of Life Cycle Analysis CO_2 emission factors could be also considered. However, for a better comparison with other studies developed in EnergyPLAN, the previously mentioned emissions factors are used in the calculations. EnergyPLAN simulates energy systems based on certain objectives such as balancing the demands for heat and electricity within the system or minimizing operating costs [43]. Model is focused on interactions and synergies between the sectors such as power production, heating, cooling, gas supply, transport, water supply and industry. EnergyPLAN is set by the user with different types of inputs and, based on these inputs, the software simulates the energy system based on user-defined and predefined criteria to identify the energy system outputs [44]. The inputs used by the user are the energy demand, the capacities and efficiencies of the plants already present or to be installed, the use of fuels, the CO_2 emissions associated with the different fuels and the costs of energy conversion technologies. EnergyPLAN requires hourly distributions to be inputted regard the electricity demand, the residential heating energy demand, the electricity import-export, the productivity of renewable-based production units. Furthermore, the user has the possibility to choose the simulation strategy and how to manage excess electricity.

EnergyPLAN offers two principal management strategies for the energy system. The first is the technical simulation strategy, for which the main objective is to reduce fuel consumption. The second simulation strategy is market-economic simulation, so EnergyPLAN simulates the energy system based on short-term marginal costs of a unit, which is the cost for which there is enough energy to meet the demand. In the present study the technical simulation line was chosen, in order to reduce the fuel consumption as much as possible. Specifically, the selected technical simulation aims at balancing the heat demand so that heat pumps and electric boilers seek to utilize only the Critical Excess Electricity Production (CEEP). In particular, CEEP refers to the full amount of energy which is exceeding the electricity needs and the interconnection capacity which, with this strategy, is diverted to electric heat production systems.

Scenario approach was used to investigate the possible lines of development of the energy system. The principal scenarios are formulated:

1) Business as usual (BAU) scenario, following the strategic documents already adopted for the investigated area;
2) Scenarios with high RES integration with the aim to achieve new goals of EU climate and energy framework.

The benefit of the analysis is the increase in knowledge on which trajectories and dynamics of energy transition would be a good fit for larger island energy systems in locations such as Mediterranean.

The objectives of the method are pursued through six fundamental lines of action:

i) implementation of RES electricity production;
ii) electrification of domestic heating systems;
iii) disposal of petrol, methane and liquefied petroleum gas engines in the regional vehicle fleet, in favour of hydrogen engines and electric vehicles;
iv) electrification, where possible, of industrial processes;
v) implementation of efficient energy storage systems;
vi) the use of biofuels (biogas/biomethane, ethanol in maritime and road transport sector, which represents the expansion from the usual consideration of an island energy system, aimed at investigating the possibility to maximise the use the local RES potential

4. Modelling the Energy Scenarios: The Sardinia Case Study

Sardinia counts approximately 1.66 million inhabitants and consists of about 2000 km of sand coast and the inland is mainly mountainous. Tourism is the driving economic activity of the Region, especially in the summer, thanks to the countless natural beauties present in the area. The regional industrial framework includes petrochemical industries and large refineries for the processing of crude oil, which are currently among the largest in Europe [45]. Furthermore, in the island, oil platforms are operating on behalf of Saipem. Other industrial sectors are the food production sector, linked to the processing of livestock products (cheese, milk, meat) [46] and fishing (tuna processing [47]), manufacturing, cork processing, mechanisation [48] (production of agricultural vehicles, shipbuilding, aircraft components), construction and metallurgy [49]. For the year 2017, selected for the reference model, the total primary energy supply for the island amounts to 45.95 TWh according to the statistics of the International Energy Agency [50]. In particular, the total primary energy supply comes from 33.65% from oil, 26.25% from coal, 24.45% from natural gas, 9.55% from biomass and 6.1% from renewables. In the same year, 27.4% of the overall electricity production was satisfied by RES, specifically 77.46% from wind, 15.49% from hydro and 7.05% from photovoltaic. The report drawn up by Terna for 2017 [51] states that the total annual electricity demand amounted to 8761 GWh, while the electricity production amounted to 11550 GWh, leaving 2789 GWh of electricity for export (24%) and 785 GWh of electricity was imported (6%). This occurs through two connection systems: SACOI (SArdinia-COrsica-Italy) and SAPEI (SArdinia-PEnisola Italiana) of 400 MW and 100 MW of capacity.

The same document [31] provides the percentage of electricity production by technology, net of losses, as shown in Table 1.

Table 1: Percentage electricity production by technology in Sardinia in 2017

Technology	**PP**	**Wind**	**Hydro**	**Photovoltaic**
%	82%	14%	3%	1%

The heat demand for space heating and domestic hot water was covered, according to the National Institute of Statistics [31], by biomass boilers, oil boilers, natural gas boilers and heat pumps.

Sardinia is not connected by pipelines to the Italian mainland and, since it does not have a methane pipeline system, Sardinia cannot rely on natural gas in the typical national percentages; for a mainly economic reason, inhabitants still make extensive use of biomass boilers, given the availability and relative cheapness of this fuel. Actually, a pipeline system for the city distribution networks, still mostly under construction, is present in the territory with the final aim of bringing methane to all users; this distribution network temporarily exploits propane or other mixtures other than methane [52]. Table 2 shows the percentages of residential demand for space heating and DHW covered by technology in Sardinia in 2017.

Table 2: Percentage of residential demand for space heating and DHW covered by technology in Sardinia in 2017

Technology	Heat Pumps	Biomass Boilers	Oil Boilers	N-Gas Boilers
%	35.34%	31.37%	17.67%	15.62%

The transport sector holds great importance in the matter of energy planning, being a sector that is not only particularly energy-intensive, but also strongly impacting on the balance of polluting emissions into the atmosphere. The Sardinian vehicle fleet consists of petrol, diesel and liquefied petroleum gas engines, both for public and private transport, with a total lack of electrical alternatives in the area [53]. In 2017, the yearly total fuel consumption for transportation is 11.8 TWh. Table 3 shows the energy consumption by sources in the transport sector in Sardinia in 2017.

Table 3: Energy consumption by sources in the transport sector in Sardinia in 2017

Fuel	Unit [toe]	Unit [TWh]
petrol	232105	2.7
diesel	629937	7.3
LPG	153802	1.8

Regarding the energy supply system, the total installed power of thermoelectric power plants, wind farms, solar PV field and hydroelectric is 1836 MW, 974 MW, 95 MW, 64 MW, respectively. The fossil fuels used to supply all the power plants are coal for 53%, oil for 13% and natural gas for 34%.

To predict the hourly production distribution of the renewable energy sources, the hourly data of PVG and METEONORM software in terms of irradiation, ambient temperature, humidity and wind speed are used. The hourly distribution of the urban waste production at 2017 is also evaluated, and by taking into account the average heating value of the urban waste and the electric conversion efficiency, the yearly production of 20 GWh by the waste incineration is estimated.

It should be noted that the energy costs related to the supply of fresh water for the island are not been taken into account in the present study. The islands water supply partially derives from surface water stored and regulated by the numerous reservoirs on the island, by means of artificial basins, (57%) and partially from underground sources of supply (43%), i.e. the aquifers present in the subsoil. Regarding these aquifers, 56% of groundwater is pumped through extraction wells, while the remaining 44% is accessible from natural springs [54].

5. Model validation

In order to estimate the accuracy of the created model, the results of the reference model are compared with historical data. This allows verification of the distributions used in the model. Therefore, to validate the model two particularly significant parameters sensitive to the variation of the energy system are considered: Total Primary Energy Supply (TPES) and CO_2 emissions. The results are considered acceptable for deviations lower than 5%. The value of TPES obtained by the developed model, equal to 42.04 TWh/year is compared with the value calculated with the elaborated of the statistics database of the International Energy Agency for 2017 [25], equal to 45.95 TWh/year (deviation of 3.91%). The net CO_2 emission value for use of coal, diesel, natural gas, LPG and urban waste resulted from the model is 9.89 Mt and is compared with the data for 2017 of the Emission Database for Global Atmospheric Research (EDGAR) database [34] equal to 10.05 Mt (deviation of 0.16%).

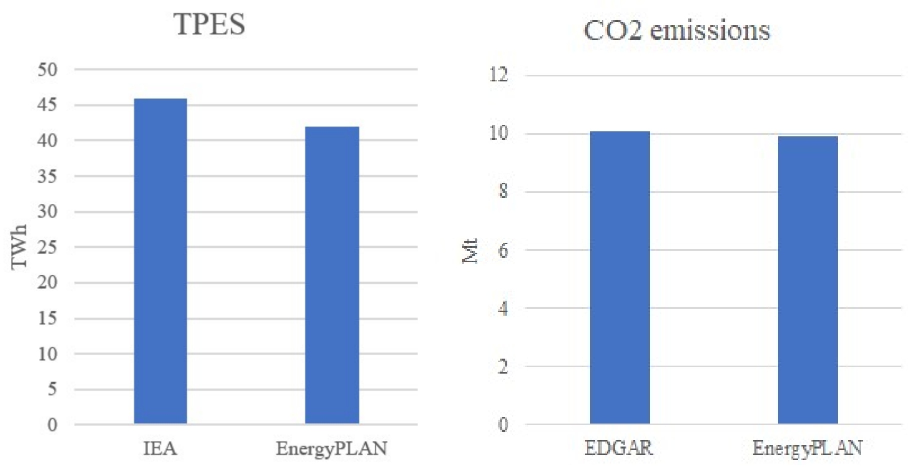

Figure 2. Primary energy comparison (left) and CO_2 emissions (right) at 2017, historical data vs the model

6. Future scenarios

6.1. Business as usual scenario

The first scenario, called "BUSINESS AS USUAL (BAU) SCENARIO 2030" is developed to address the guidelines of the Energy and Environmental Plan of the Sardinia Region (REEP), indicating several energy measures for the reduction of CO_2 emissions of 50% by 2030 compared to the values estimated in 1990. In the plan the following General Objectives (OGs) are identified: OG1. Transformation of the Sardinian energy system towards an integrated and intelligent configuration (Sardinian Smart Energy System); OG2. Energy security; OG3. Increased efficiency and energy savings; OG4. Promotion of research and active participation in the energy field. To address these OGs, the following technical strategies are implemented for each energy sector (Figure 3).

Heating sector
1.Increase of 20% in the efficiency of buildings isolation;
2.Reduction in LPG, biomasses and oil fueled applications;

Electricity sector
1.Self-consumption of electricity production from household-installed RES;
2.Decommissioning of 876 MW of thermoelectric power plants running on coal and oil.

Transport sector
1.Reduction of diesel and petrol consumption;
2.Replacement 50% of petrol cars with Plug-in Hybrid Vehicles and Battery Electric Vehicles;
3.Conversion to methane of the fleet of hybrid LPG cars;
4.Encouraging the use of car-pooling, car sharing and public transport

Figure 3. Technical strategies of the BUSINESS AS USUAL SCENARIO 2030.

For the heating sector, refurbishment of buildings envelopes by adding thermal insulation is taken into account, considering that the heating demand decreases by 20% with respect to demand of the 2017 reference scenario. In the reference model, the total demand for domestic heating and hot water accounts to 7.81 TWh, in the BAU scenario and the expected demand drops to 6.25 TWh (0.25 TWh of the expected demand is provided by the installation of solar thermal collectors, as required by point 3, Figure 3).

The installed capacity of dispatchable units in the Sardinian energy system in the assumed configuration of the BAU scenario is 960 MW, compared to the 1836 MW of 2017 (Figure 3). The evaluations related to the expected electricity consumption in the Sardinia Region are developed considering the forecasts of electricity demand published by Terna; the final result on regional electricity consumption is a reduction of about 14% with respect to the value recorded in 2014. This means that a yearly consumption of 7.2 TWh is expected by 2030. The instantaneous flexible consumption of the excess energy from RES would enable local increase in share of RES, determining a direct profitability for both the producer and the user; reduction of the transmission congestions, consequently reducing the impacts on the regional electricity energy system, thus allowing the physical constraints to be relaxed. The implementation of the proposed flexible consumption hypotheses leads to an apparent yearly consumption of 6.1 TWh.

For the transport sector, according the suggestions provided by REEP, a reduction by 20% in terms of yearly amount of fuel for diesel engines and 50% for petrol engines is envisaged. Moreover, a total decommissioning of LPG vehicles is considered, with the use of 400 GWh of methane for transport purposes and 91.5 GWh of electricity to supply dump charge electric vehicles.

The results of the technical strategies implemented in EnergyPLAN are compared with the forecasts of the REEP. In terms of total primary energy consumption from fossil fuels, the model implemented underestimates this consumption of about 3.7%, with a total primary energy consumption expected by 2030 of 31.3 TWh/year (Figure 4). The results are obtained by considering the following assumptions: the Saras refinery consumption are not taken into consideration, while the consumption related to air and maritime transport sector from and to the continent is considered only for 50% attributable to the Sardinia Region.

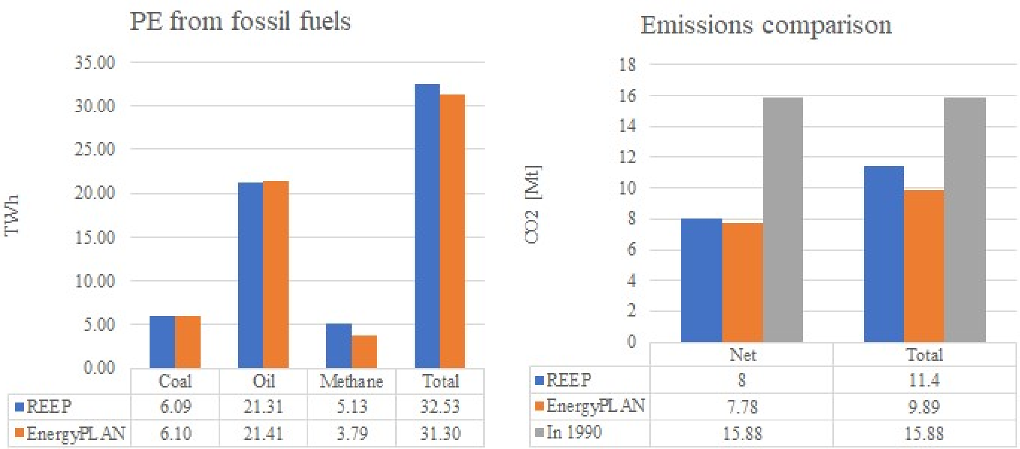

Figure 4. Primary energy consumption from fossil fuels, BAU model vs REEP forecast (left); total and net CO_2 emissions comparison, BAU model vs REEP forecast and vs 1990 level (right)

The total and net CO_2 emissions values by 2030 obtained by model are compared with the REEP forecast and with 1990 emission value, assumed as reference value, in order to verify the achievement of the objectives indicated by the Kyoto protocol and those indicated by the European Commission and defined as regional strategic objectives for Sardinia. The analysis clearly shows that, comparing the total emissions produced in Sardinia, BAU scenario does not suffice to achieve the minimum indicated target. Note that the net emissions are only related to the local primary energy consumption. Such parameter is crucial to assess the actions to be locally implemented in order to reduce the emissions of that specific region. In fact, the net and total emissions in 1990 are coincident due to the fact that all the energy was produced within the island borders. Therefore, the net emissions represent the effective transformation of the Sardinian energy system in terms of reduction in emissions, consumption, production from RESs and infrastructural transformation. Therefore, net emissions will be the indicator for the evaluation of the objectives of the present REEP. In this case, the emissions reduction by 50% is achieved both in the scenario proposed by the plan and in the modelled BAU scenario. The analysis of Figure 4 clearly shows the effect of the proposed actions (Figure 3) on the reduction in net emissions, compared to the total ones. In conclusion, there is a deviation between the total emissions foreseen by the plan and those modelled by the software of 13%. The obtained net emissions are almost coincident, as proof of the model ability to correctly simulate what happens within the regional system.

6.2. High RES integration scenario

Next scenario is identified as “High RES scenario” in years 2030 and 2050. High RES 2030 scenario takes into account the three main objectives addressed with the "2030 Climate and Energy Framework": i) the reduction of at least 40% in greenhouse gas emissions (compared to 1990 levels); ii) a share of at least 32% of renewable energy; iii) the improvement of at least 32.5% in energy efficiency. The mentioned targets will represent intermediate targets towards the complete decarbonisation envisaged by the European Community by 2050. To reach the objectives of High RES 2030 scenario, the following actions are implemented in EnergyPLAN model:

- the complete disposal of coal;
- disposal of all fossil fuels in the transport sector;
- double the percentage of primary energy from RES compared to value of the BAU scenario (i.e. from 21% to at least 42%).

For the electricity sector, in order to reach 40% of primary energy from RES, two key energy actions are implemented. Firstly, 610 MW of traditional thermoelectric power is expected to be divested, compared to the 960 MW envisaged by the plan. For the 350 MW thermoelectric power plants still installed, it is supposed that they are fuelled by natural gas, the least impacting among the hydrocarbons. Secondly, the installed PV plants are doubled and the installed wind farms are increased by 50%, according to the ENTSO-E forecast [55], estimating a 120% growth in installations for RES production in the years between 2020 and 2030. Overall installed capacities of electricity generation technologies are given in Figure 5.

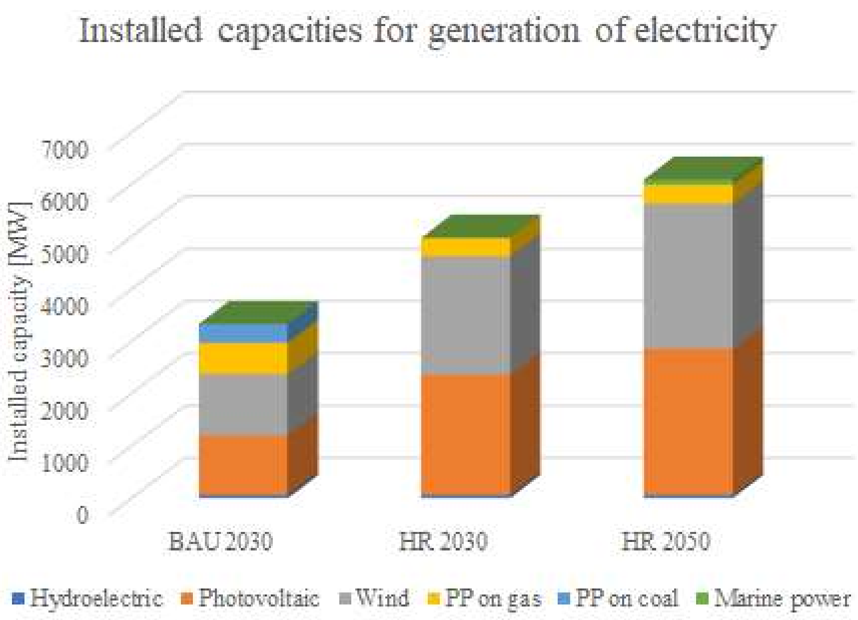

Figure 5. The installed capacity by type of plant in future scenarios

The predominant use of the RES leads to typical issue of balancing the variable production. Therefore, the flexibility of conventional production units is required to rapidly replace RES production and meet peak evening demand. The possible use of storage devices or the construction of new pump-hydro stations is a key priority for the balancing of the system.

As regards the transport sector, the vehicle fleet by 2030, according to the REEP forecasts, consists of a share of electric vehicles in *dump charge* mode and electric vehicles in *smart charge* mode, consistent with the benefit of the use of EV's battery storage systems. In EnergyPLAN, these energy actions are implemented by setting the share of vehicles connected to the grid during peak demand at 20%; the connection capacity of G2B (grid to battery) and B2G (battery to grid to) at 1750 MW; the efficiency of transmission at 90%; the battery storage capacity at 25 GWh, with the hypothesis of keeping the overall number of billion km/year for road transport unchanged. The battery storage capacity of each vehicle is set equal to 50 kWh and it is considered that each vehicle is connected to a domestic power system of 3.5 kW. Therefore, the calculation of the overall electricity storage capacity of the smart-charge electric vehicle fleet and the minimum power that must be available on the network for charging these vehicles is obtained. To simulate the use of hydrogen vehicles and therefore, of the electrolyser (for the production of pure hydrogen), the capacity of the electrolyser and hydrogen storage must be defined. In this work, the assumed electrolyser and hydrogen storage capacity is 790 MW and 4 GWh, respectively; the conversion efficiency of electrolyser is around 73%. Note that when these energy actions are implemented, the maximum value of import and export recorded in the year must not be higher than the maximum transmission line capacity (1400 MW).

Therefore, technical simulation strategy is selected to maximize the regional use of the exceeding production. It is supposed that heat pumps and electric boilers "seek to utilise all electricity export" and the sub-strategy "V2G seeks to balance the conventional power plants and all electricity import and export". With this assumption, the maximum hourly import value is limited to 1209 MW and maximum hourly export value is 1380 MW, both within the physical limits of the transmission system with the mainland.

High RES scenario 2050 is implemented with the overall goal to reach zero emissions by 2050, or *carbon neutrality*. Demographic forecasting and electricity and heat demand forecasting, that were already provided by 2030 in REEP are used as inputs for this scenario. Through the projections of the National Institute of Statistics (ISTAT) [31] the likely number of the regional population in the reviewed year was deduced, measuring a reduction of about 300,000 units compared to 2030, bringing the count down to 1,365,896 inhabitants. For both heat and electricity demand forecasting, the per capita consumptions regarding the year 2030 were considered. The overall yearly electricity demand amounts to 6 TWh.

Compared to the high RES 2030 scenario, 50 MW of thermoelectric have been decommissioned; 300 MW fuelled by natural gas, remained in operation, for peak coverage. The innovation to 2050 is the introduction of biomethane as fuel for traditional thermoelectric power plants. The goal is the integration of urban waste into the energy system in a more inclusive and efficient way than the state of the art of previous years. In this scenario, the organic fraction of urban solid waste is selected and used as substrate for the production of biogas from anaerobic digestion. For the base load, in competition with the production units from renewable sources, the installation of 60 MW thermoelectric is planned, using waste as the fuel. To secure the balancing of the system based on of photovoltaic and wind power, which make the system's supply variable, an expansion of the Taloro hydroelectric power station was planned which, as early as 2030, represented a fundamental contribution to electricity storage. The power of the installed turbine/pump unit has increased up to the value of 500 MW, obtaining a storage capacity of 10 GWh.

The entire west coast of Sardinia is characterized by values of wave production higher than 12 kW/m and the area where the highest values are reached is located north of Alghero. Therefore, the installation of 100 MW of turbines for the production of electricity from the waves was foreseen; according to the documents of the 17th ASITA National Conference, the North West coast of Sardinia is the most suitable site for the installation. With a power value such as the one chosen, the turbine encumber would affect a stretch of coast about 7 km long.

In the domestic heating sector, a reduction in the thermal energy demand required annually by 20% compared to the value of 2030 is assumed, following the implementation of efficiency and insulation strategies for the housing units. The thermal of households is 3.81 TWh, which is calculated by using the same rate of reduction in demand for periods 2015-2030 and 2030-2050. The reduction quota was calculated with the value of the demand of thermal energy per capita and then converted into global data for the Region. To produce the required amount of thermal energy, assuming a heat pump Coefficient of Performance (COP) of 3, a necessary electrical input of 1.27 TWh was calculated. This input energy value is reduced by 12.6% due to the planned installation of solar thermal heating support systems by 25% of the users, significantly increasing the percentage of users equipped with solar thermal collectors that in 2030 is expected to be of 5%. Using this system, the electrical demand for the production of thermal energy for the purpose of residential heating drops to 1.11 TWh.

To exploit the synergies between transport and power production sectors, smart charge electric vehicles and V2G are used, disposing of a large part of the hydrogen ones. In particular, smart charges in this scenario go from meeting 50% of the total transport demand to 75%; hydrogen vehicles, on the other hand, see a 45% reduction in their use in the regional vehicle fleet. The capacity of grid to battery connection must therefore be expanded from 2000 MW to approx. 3000 MW, to make up for the growing number of vehicles that, not only need charging, but also must be able to use these vehicles as storage units for electricity. In doing so, the overall battery storage capacity raises from 31 GWh to 47 GWh.

In industrial sector, the fuel switch was carried out keeping the total of primary energy input constant, while any contribution of oil products was eliminated, with final mix amounting to 30% of biomass, 60% electricity and the remaining 10% fuelled by hydrogen. Biogas consumption has been halved compared to the value in force in 2030 and has been replaced 50% by electricity and 50% by hydrogen. To satisfy this further request for hydrogen, an additional 80 MW of electrolysers are envisaged for its production.

6.3. Discussion of the use of biofuels

The last step considered in the energy transition of the large islands is the possibility to use local potential for the production and use of biofuels: biogas/biomethane and ethanol in maritime and road transport sector applications. The additional demand for the maritime transport from and to Sardinia is calculated according to the following data, summarised in Table 4, and it is equal 2.22 TWh. Note that only the main routes from and to Sardinia are considered, for one of the mail ship companies [56].

Table 4: Data for the evaluation of the primary energy demand for maritime transport

Routes	Distance [km]	Routes for week [-]	Yearly distance 10^3[km/year], from and to
Cagliari-Salerno	523	3	163
Cagliari- Valencia	860	3	268
Cagliari- Palermo	422	3	132
Cagliari-Genova	680	5	354
Cagliari- Livorno	566	5	177
Olbia- Livorno	300	14	437
Olbia- Civitavecchia	236	7	172
Porto Torres-Genova	400	3	125
Porto Torres- Civitavecchia	330	5	172
Porto Torres- Barcellona	550	5	286

Therefore, the total distance is 2284 10^3 [km/year]. Considering a travel velocity equal to 29.5 km/h, the lower heating value of the fuel, equal to 11.76 kWh/kg (10 kWh/l, density 0.85 kg/l), the primary energy demand equal to 2.22 TWh/year is obtained. The variation of the frequency of the routes, as a function of the season, is also considered.

The road transport is considered to have the same demand as in previously described scenarios. The dynamics of such use are considered discussing the previous scenarios as follows (with “BIO” designating the addition of biofuels):

- 2030 BAU BIO
  - 33% of the remaining diesel and petrol are replaced by biofuels
  - 3% of maritime transport uses biomethane
- 2030 HR BIO
  - 33% of the remaining diesel and petrol are replaced by biofuels
  - 3% of maritime transport uses biomethane
- BAU 2050 BIO
  - 100 % of transport is supplied from bioethanol and biomethane
- HR 2050 v1
  - Part of transport demand previously supplied by hydrogen is now supplied with bioethanol and biomethane
- HR 2050 v2
  - Part of transport demand previously proposed as V2G is now supplied with bioethanol and biomethane

The data on the production of bioethanol for the use in road transport sector is provided in Table 5.

Table 5: Bioethanol for transport in relation to the land use on Sardinia

Bioethanol for transport in relation to the land use	
Proposed cover factor (-)	0.10
Demand (TWh/year)	11.80
Producibility scorn stalks (t/ha year)	0.70
PCI ethanol (kWh/kg)	7.53
Primary energy from bioethanol (kWh/ha year)	5269.44
Land tot (ha)	223932
Land tot (km^2)	2239
Land (%)	9%

Also, for the maritime transport, the land relation to the production of biomethane is given in Table 6.

Table 6. Biomethane for maritime transport

Biomethane from silage maize						
Biogas (m^3/ha day)	Biogas for year (m^3/ha)	Primary energy (biomethane) (kWh/ha year)	Land tot (ha)	Land tot (km^2)	Total area Sardinia (km^2)	Land needed (%)
32	11680	72807.28	27168.76707	271.6876707	24100	1%

7. Results

Results for all scenarios are given in Table 7.

Table 7. Summary results table for the proposed scenarios

	BAU 2030	**BAU 2030 BIO**	**HR 2030**	**HR 2030 BIO**	**BAU 2050 BIO**	**HR 2050**	**HR 2050 v1**	**HR 2050 v2**
Electricity from RES (%)	79.70	79.4	100.50	89.00	95.90	110.80	125.6	131.9
Electricity from RES (TWh/y)	4.90	4.93	10.60	8.24	7.90	13.20	13.18	13.35
PES from RES (%)	21.10	28.10	42.80	44.60	93.70	93.90	95.1	95
Total fuel consumption (TWh/y)	42.83	42.69	32.99	33.36	26.93	16.52	19.16	25.71
PES in transportation (TWh/y)	7.93	7.93	3.39	5.99	7.80	2.80	4.3	7.4
Total emissions (Mton/y)	9.89	8.42	4.63	4.54	0.37	0.23	0.209	0.298
Net emissions (Mton/y)	7.78	6.85	4.63	4.50	0.35	0.00	-0.605	-1.296
Import (TWh/y)	0.00	0.00	0.73	0.06	0.15	0.52	0.19	1.04
Export (TWh/y)	2.76	2.08	0.93	0.33	0.19	1.12	1.98	4.55
CEEP (TWh/y)	0.00	0.00	0.04	0.00	0.00	0.16	0.38	0.46

Most relevant factors are analysed in further discussion: electricity demand, fuels in the transport sector, net and total emissions, import-export and CEEP. The electric devices for domestic *heating* go from covering 27% of the individual thermal energy demand with an electricity consumption of 0.53 TWh per year in the scenarios of 2030, to covering 96% of the thermal demand, increasing energy consumption to just 1.11 TWh annually in 2050 (Figure 6).

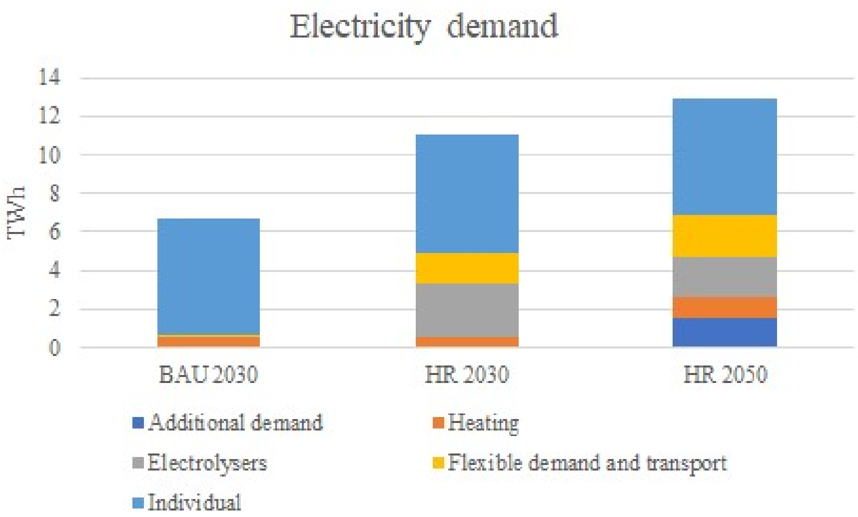

Figure 6. Electricity demand in the future scenarios

The amount of electricity produced from renewable energy sources grows in the three scenarios from 80% to 101% to 111% (Table 7); with share larger than 100% being expressed by the software due to comparison of the electricity produced by the RES to demand for electricity. This amount becomes 89% and 96% in HR 2030 BIO and BAU 2050 BIO scenarios, respectively.

By exploiting energy from renewable sources to, for example, produce hydrogen from electrolysers, a surplus is created which is not conveyed directly to the user as electricity but in other forms, decarbonizing other sectors. In HR 2050 scenario there is a strong increase in smart charge electric vehicles and a reduction in hydrogen vehicles compared the HR 2030 scenario (Figure 7). Also, in the scenarios that rely on locally produced biofuels, their use increases TPES in transport compared to scenarios with mainly electrified transport, but also increases the PES from RES.

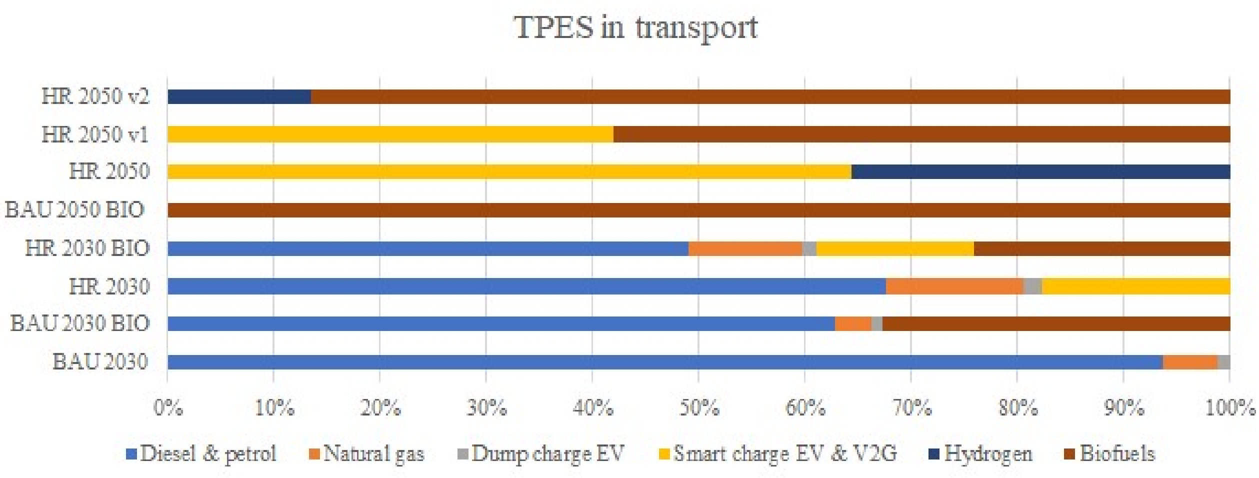

Figure 7. Evolution of the primary energy supply in transport in future scenarios

This apparent reversal of trend is fully explained considering the need, in the 2050 system, for an energy storage system that would be the most immediate and easily usable by users; V2G systems not only provide immediate coverage of production surpluses without the need for transformations, but also interact directly with users. Electrolysers for the production of hydrogen can exploit the aforementioned surplus of electricity, but they are subject to efficiencies that involve a loss in energy terms, needing additional transformation to be able to produce electricity, as the electricity has been transformed into a different energy vector, hydrogen. The complete disposal of fossil fuels in the industrial, transport and electricity and thermal energy sectors can only lead to a balance of CO_2 emissions that is practically zero (Figure 8). The total emissions in BAU scenario of 2050 using biofuels are considerably low, equal to 0.37 Mton/year. Considering the same scenario but for 2030 BAU 2030 BIO, total emissions pass from 9.89 Mton/year in BAU 2030 scenario to 8.42 Mton/year. This is mainly due to the reduction in the total fuel consumption, passing from 42.83 TWh/year in BAU 2030 to 26.93 TWh/year in BAU 2050 BIO (Table 7).

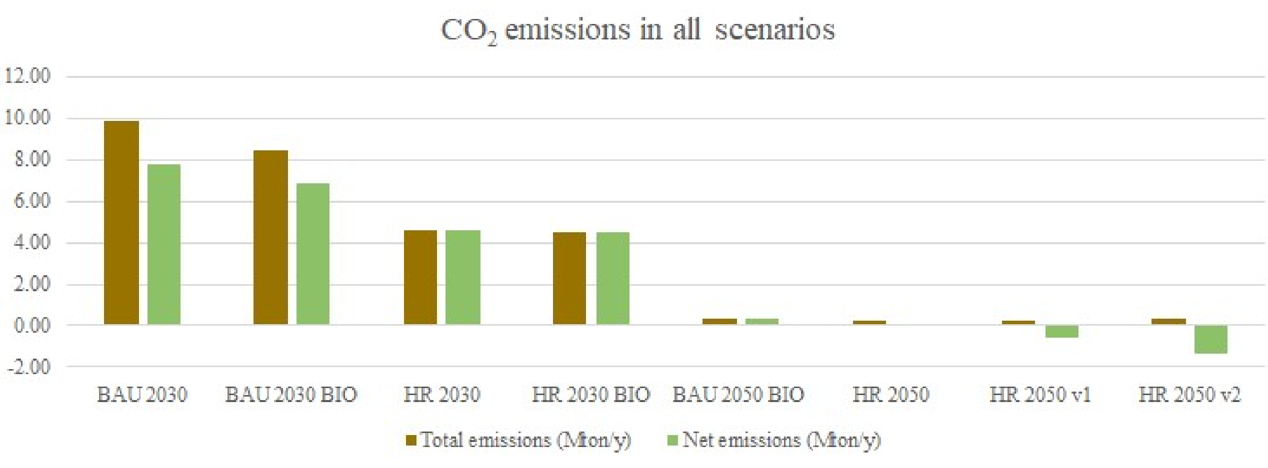

Figure 8. CO_2 emissions in future scenarios

In particular, the decarbonisation of the industrial sector was qualitatively envisaged through, first of all, the electrification of the processes, where possible, in order to exploit to the maximum of its potential the massive installation of renewable energy sources. Alternatively, for the processes that cannot be subjected to electrification, a transition to a "clean" and efficient fuel, hydrogen, has been envisaged. The big advantage of using hydrogen is that it can be considered as second-hand RES electricity since it derives from electrolysis processes fuelled by the surplus production of RES plants. Comparatively, scenarios that rely on biofuels do not reduce CEEP as effectively, but it stays withing the economically feasible limit of 5% of electricity demand.

The highly energy-intensive sectors must undergo radical changes to reach this state of climate neutrality and thus fulfil the European goal by 2050.

Last significant parameters are import, export and CEEP, shown in Figure 9. It is noticeable that HR 2030 and HR 2050 scenarios are better balanced for the local energy needs and that the CEEP, representing curtailment of newly installed variable RES units is negligible. The only increase in CEEP occurs for the scenario that relies on the biofuels instead of electrification of transport, but for the chosen configuration the CEEP remains acceptable even in such case.

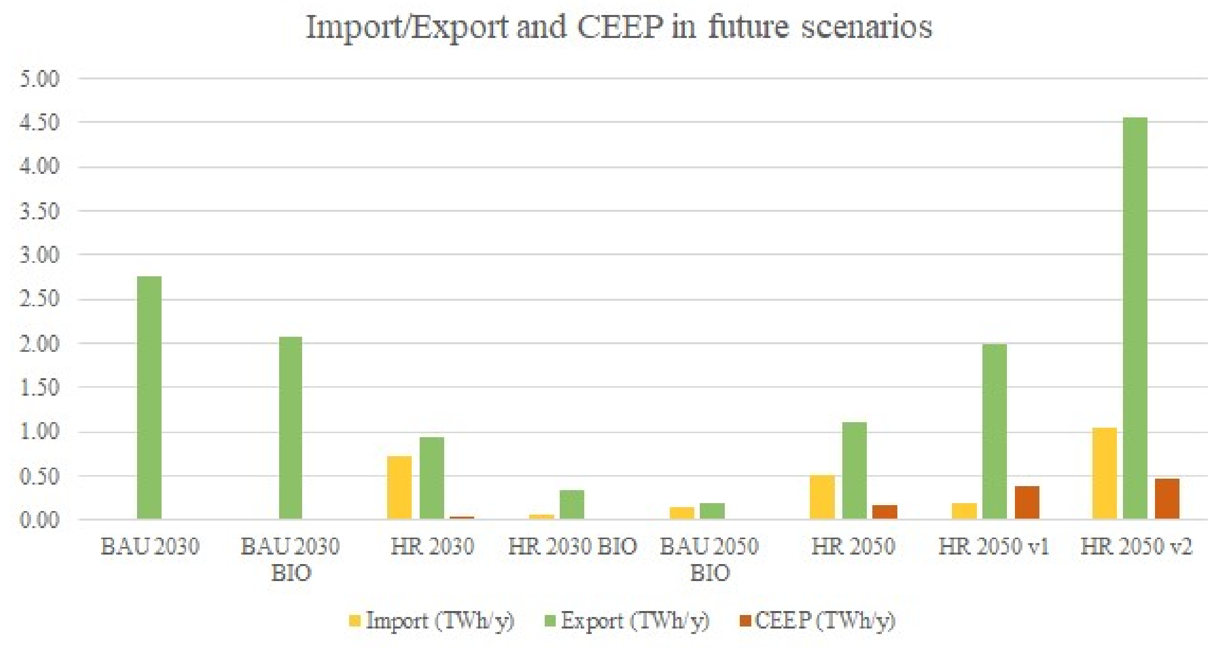

Figure 9. Import/Export and CEEP for future scenarios

8. Conclusion

In this paper, the development of an energy planning model for the analysis of different future energy scenarios for island systems is presented. The model is applied to the case study of the Sardinia region (Centre of Italy). The developed model is validated considering two significant parameters: Total

Primary Energy Supply (TPES) and CO_2 emission. Three future scenarios are analysed: i) the "Business As Usual (BAU) scenario 2030" showing several energy measures (such as the development of a smart energy system, energy security, energy saving and efficiency) for the reduction of CO_2 emissions of 50% by 2030 compared to the values estimated in 1990; ii) High RES 2030 scenario consistent with the "2030 Climate and Energy Framework"; ii) High RES scenario 2050 considering the overall goal to reach zero emissions by 2050, or carbon neutrality. The results achieved by the model are analysed by comparing the following key parameters: electricity demand, fuels in the transport sector, net and total emissions, import-export and critical excess electricity production. The implemented actions resulted in an increase of the share of RES in the electricity sector from 80% (BAU) to 101% (High RES 30) to 111% (High RES 50), respectively, including the exported energy. The alternative option of relying on the locally produced biofuels was also investigated and the possibility to secure energy supply for transport in that way was found to be only slightly less favourable from the energy systems' stability perspective. Results also show an increase of the smart charge electric vehicles and a reduction of hydrogen vehicles passing from High RES 30 to High RES 50, due to the inefficiency caused by the conversion of the electricity into hydrogen. Therefore, the direct use of the electricity is considered as better choice to minimize these losses. To fulfil the European goals by 2050, the complete disposal of fossil fuels in all the energy-intensive sectors (industrial, transport and electricity) is mandatory. The implemented actions are described in detail in the paper, leading to an optimal balance of the local energy need so that the resulted critical excess electricity production is negligible. The method implemented in this study as well as the dynamics of energy transition and the relative energy measures to achieve the objectives addressing the carbon neutrality can represent an optimal reference for larger island energy systems located in the Mediterranean Sea. Future work includes coupling the present method with the economic parameters in order to correctly weight the advantages of the investigated scenarios and resulting energy systems' configurations.

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