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Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources

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ABSTRACT

Islands' energy systems present a challenge in energy planning due to a limited amount of resources which could be used to make islands self-sufficient and sustainable. This paper presents a novel approach for defining energy system of a carbon neutral island which utilizes only intermittent renewable energy sources in combination with vehicle-to-grid concept as a demand response technology, where marine transportation has also been taken into account. Integration of power, heating, cooling and transport sectors has been modelled by using EnergyPLAN tool, i.e. its updated November 2017 version which is capable of simulating vehicle-to-grid operation in mentioned conditions. Power supply capacities have been selected not by using scenario analysis but by implementing an optimization procedure based on series of simulations in EnergyPLAN tool. In order to choose the most suitable power supply system configuration, two boundary conditions have been defined. Firstly, only solar and wind capacities must be utilized. Secondly, total electricity import and export must be balanced, i.e. the island has to be CO_2 neutral. In order to validate the approach, Croatian Island of Korčula has been used as the case study. 2011 has been selected as the base year for which final energy consumption has been calculated. The final simulation year was set to 2030 in which optimal capacities are installed. It has been shown that configuration with 40 MW of wind and 6 MW of installed solar capacities presents the least cost solution, while 22 MW of wind in combination with 30 MW of installed solar capacities provides the lowest amount of total electricity import and export. Analysis of the vehicle-to-grid share reduction has shown increase in total import and export in both cases, while transmission peak loads have not been influenced.

1. Introduction

A large majority of island communities are traditionally experiencing difficulties in terms of energy supply and energy security associated with a high dependency on imported fossil fuels. Growing concerns about climate change and increasing profitability of renewable based energy technologies contribute to higher shares of the renewable energy source (RES) utilization on a number of islands. Lately, a step forward in the endeavour to achieve energy self-sufficient islands has become integration of power sector with energy demand of domestic heating, cooling, fuels for transport or larger, commercial demand.

On the one hand, islands have a significantly unexploited potential for sustainable development while on the other, they are among the most vulnerable areas to experience a variety of impacts of climate change on their local ecosystem and livelihoods. Both have been recognised and acknowledged by several initiatives targeting sustainable development on islands. The International Renewable Energy Agency actively supports small island developing states (SIDS) into their renewable energy transition since 2011 [1] and coordinates the worldwide SIDS Lighthouse Initiative launched at the 2014 Climate Summit [2]. The SIDS Initiative supports energy transformation on islands from fossil-fuel based power systems enabling smart deployment of renewable energy in power, heating, cooling and transportation sectors. The European Union (EU) developed two strategies to treat climate change and sustainable development on islands under the same umbrella, namely Clean Energy for EU Islands [3] and Smart Island Initiative [4]. The latter represents a bottom-up initiative tackling climate change and supporting sustainable economic growth through a holistic approach by exploiting synergies between sectors, thus directly addressing the circular economy. Initiatives seek to gather European islands by developing a common method for the clean energy transition focusing on smart islands principles. Some researchers are also developing tools

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which could facilitate the integration of sustainable energy on islands, such as the one shown in [5].

In renewable energy planning, various options of resource and technology combinations can be applied on islands resulting in different technical and economic feasibilities. N. Duić et al. [6] developed the RenewIslands methodology specially designed to enable the assessment of alternative scenarios for energy and resource planning. The methodology supports renewable energy scenarios design through a systematic and comprehensive approach divided into four steps, namely analysis of needs, available resources, appropriate technologies and creation of scenarios. Moreover, the methodology is applied to several islands and evaluated by a computer tool called H2RES designed as a support for an island energy system modelling with the RenewIsland methodology [7–9]. H2RES was used in [8] to show how the integration of a desalination plant can support higher penetration of renewable energy sources reaching up to 72% renewable energy source production in 2020. Apart from using tools specifically designed for the islands systems, tools for different area sizes have proven successful in modelling island systems. The EnergyPLAN tool designed for national or regional energy planning was used in a number of case studies, i.e. La Gomera (Spain) [10], Thai island Wang-an (Taiwan) [11], Vis, Lastovo, Korcula [12], Mljet [12,13] and Hvar [14] (Croatia) while the HOMER tool developed for local community and single project energy systems has been applied on island systems such as Agios Efstratios (Greece) [15], St. Martin (Bangladesh) [16], Prince Edward (Canada) [17] and Vis (Croatia) [18]. The comparison of different tools for modelling the energy system on islands given in D. Neves et al. [19] highlighted the importance of the demand response to improve energy systems performance.

A rapid development of sustainable energy technologies along with favourable conditions for the exploitation of RES on a number of islands results in cost effective utilization of renewable energy in comparison to the solutions based on fossil fuels. A number of studies provided feasibility analysis of either individual technologies or their combinations and proposed novel methodologies and tools especially designed for the islands. The results of techno-economic analysis of different energy storage systems to support RES energy generation on islands showed financially viable electrification solutions [20]. P. Blechinger et al. [21] performed a techno-economic assessment of almost 1800 small islands proving the high market potential for the solar PV, wind power and battery storage systems. The economic feasibility of high wind energy share at island level was shown in [22]. The study is of particular interest for designing a cost-effective system to support a national energy strategy with a high RES share. The analysis of the combination of different desalination and solar technologies in a stand-alone microgrid with high RES penetration resulted in lower overall cost comparing to the fossil fuel based solutions [23]. Moreover, solutions such as a demand response strategy for a domestic hot water system in RES based microgrids proved to be a beneficial solution to reduce peak load and cost increase [24]. In [25], Anoune et al. analysed the importance of the optimization sizing technique to achieve maximum power reliability and the minimum system cost of a hybrid renewable energy system. A methodology for an assessment of the wind potential and costs on islands was presented in [26] while [27] presented a methodology for the economic assessment of roof PV systems. Schallenberg-Rodriguez presented a method for techno-economical potential of PV installation on the roof with the case study of the Canary Islands [28], while Reinsberger and Posch presented main drivers and barriers for PV projects [29]. In order to support short and long-term RES energy planning scenarios F. Guzzi et al. [30] designed a tool for economic assessment and support in investment planning. Economic assessment for integration of solar and geothermal energy for an island system which simultaneously produces electricity, thermal and cooling energy, including fresh water has been studied in [31].

Modelling renewable energy systems for self-sufficient islands requires special attention to be placed on the balancing of the renewable energy generation. Different energy systems have been designed in order to balance the variable nature of electricity generation from solar and wind. The great overview of island energy systems which proves the interest in renewable energy system designs can be observed in reviews [32,33] and [34]. A high share of renewable energy sources can be achieved by utilising typical energy storage technologies such as batteries and hydro storage. Marczinkowski et al. [35] analysed technical feasibility of PV systems coupled with batteries on the case of two approaches for a consumers' involvement in the smart island energy systems development. Both solutions, batteries at the residential households and the communal battery, showed to have a great potential for the implementation if the technological specifications are well coordinated and controlled. A cost benefit analysis of photovoltaic generators and the appropriate energy storage solution, namely batteries or hydro storage was performed for 33 Aegean islands (Greece) of different sizes [36]. Both storage technologies were also evaluated in [37] and [38] for a remote island in Hong Kong. Furthermore, the integration of hydrogen as a balancing option for the island energy transition was analysed in [39].

Moreover, coupling of different sectors represents a successful approach to enable high levels of variable renewable energy sources [40]. Such integration can best be achieved through a smart energy system which enables to detect and utilize synergies between different sectors [41]. Smart energy systems thus provide a better management of variable renewable energy generation as well as their higher penetration. With a special focus on the transport sector, B.V. Mathiesen et al. [42] showed that 100% renewable energy system is technically feasible by applying the smart energy system approach. Based on the analysis of the several aspects and constraints of the high RES shares on the islands, G. Notton [43] has emphasized that optimal energy management throughout the smart grid approach is inevitable to fully accomplish islands' renewable energy development. The polygeneration system, combining electricity and water supply systems, as well as heating and cooling supply was investigated in the case study of Pantelleria island (Italy) [31]. The research showed that the polygeneration approach can fulfil the water demand of the community and supply significant amounts of electricity, heating and cooling. The importance of RES integration and storage technologies, together with energy savings and energy efficiency improvements in energy production was highlighted for the case of an island of Hvar (Croatia) [14].

Integration of various sectors and energy types can often be observed in modelling of 100% renewable energy systems since for the achievement of such systems all the energy sectors, including electricity, heating, cooling and transport must be considered. However, number of studies aimed at achieving 100% renewable energy supply took into account only power sector [11,15,17,44–46]. A feasibility study for replacement of diesel-generators with renewable energy technologies for the case of small Greek island was carried out in [15]. Due to the extreme seasonal variations in energy consumption caused by tourism industry, D. Thomas et al. [15] envisaged enormous capacity of solar and wind as well as battery storage for the case of nearly 100% renewable energy system. Moreover, they highlighted potential technical difficulties of reaching 100%, namely maintaining stable voltage and frequency in the grid. N. Maïzi et al. [44] outlined technical constraints and the need for the transmission grid reinforcement for higher integration of variable renewable energy sources in the power mix. Fully renewable power supply for the year 2030 was developed for the case of Reunion island (France, Indian Ocean) [45] prioritising biomass as the most feasible solution. Therefore, biomass represented more than 50% of total electricity generation in 2030. Variability of renewable energy generation and mismatches in the demand and production were discussed in [11] showing that 100% renewable electricity can be achieved through the deployment of storages. Storage technology was envisaged, on the one hand to store electricity surplus while on the other to provide electricity during generation deficit. Hybrid hydrogen renewable energy system for a remote island area without connection was examined in [47]. The obtained analysis aimed to provide results for fostering development of 100% renewable energy island systems. A. Khoodaruth et al. [48] analysed present and proposed energy strategies for Mauritius and went a step forward including transportation and cooling sector in the extended analysis for reaching 100% energy self-sufficiency by 2050. In this envision A. Khoodaruth et al. pointed out the crucial role of government and private sector for such endeavour. Moreover, they provided detailed analysis of renewable technologies suitable for achieving the goal of self-sufficiency. They did not develop concrete scenarios of renewable energy transition but they indicated that various circumstances such as technological developments, economic growth, government policies, and consumer response will determine the technologies and the energy mix. According to the presented literature review it can be seen that only few studies developed scenarios considering overall energy system, encompassing all energy sectors, namely, electricity, heating, cooling and transport in the island energy systems.

Even though strategies for sustainable development on islands call for comprehensive energy transition, the transport sector is often omitted or taken into account only through personal vehicles fleet [4]. While there are already proven solutions for the renewable energy generation as well as significant progress in decreasing demand in heat and electricity sectors, sustainable development in transportation sector is still being imposed as one of the greatest challenges [42]. D. F. Dominković et al. [49] analysed four main solutions for the replacement of the fossil fuels, i.e. biofuels, hydrogen and synthetic fuels (electrofuels). The review pointed out that the transport sector is rarely looked as an integral part of the entire energy system while on the other hand a number of studies dealing with the single transport modes or technological solutions exists. Although, it is confirmed that electric vehicles (EV) have better fuel economies compared to other types of vehicles, CO_2 emissions strongly depend on the electricity generation source and in case of electricity production from oil or coal-fired plants CO_2 emissions can sometimes be higher compared to the conventional gasoline vehicles [50]. Hence, the islands provide an additional advantage for transport electrification due to a high potential for electricity generation from locally available renewable energy sources. Along with passenger cars, public transport is a frequent subject of research. Moreover, there is an increasing number of public transportation electrification projects in practice. The ZeEUS eBus Report [51] reveals increasing interest in electric bus deployment with approximately 25 European cities already having published e-bus strategies for 2020. Furthermore, on the worldwide scale they estimated that more than 2 million buses were electric where China had the leading role with over 8.3% of the global total. It has also been pointed out in [49] that there is quite a low number of researches on alternative fuels in marine transport sector compared to the other sectors.

Advantages of EVs in enhancing and managing variable renewable energy sources into the energy system have been pointed out in several studies [52–54]. Initiatives for transforming island power systems into smart ones through comparison of vehicle to grid (V2G), demand side management (DSM) and stationary electricity storage systems were assessed in [55]. The assessment was obtained for five prototype islands representing nearly 60 islands and the results show that type of initiative depends on the island size where smaller islands are more suitable for renewable energy source initiative, whereas larger islands for DSM. However, more detailed analysis of each island was not given. On the island scale, A. Pfeifer et al. [56] analysed how integration of V2G technology can support higher share of RES for the group of interconnected islands. However, as the main focus of the study was on the interconnections between islands which were used as an additional flexibility option, the study did not consider self-sufficiency of each island separately. A similar study with a pathway for 100% renewable energy supply in the Canary Islands until year 2050 was presented in [57]. The analysis took into account islands' power, heat and land transportation showing that the entire demand can be covered with the local energy production. Moreover, the study included smart charging of battery electric vehicles but V2G option, i.e. batteries discharge, was not analysed in detail. Vehicle to grid option was analysed for several scenarios in Åland Islands (Finland) where not only the street vehicles but also the electrified marine transport was modelled [58]. The research focused on all the sectors, however it is important to mention that climatic differences between northern and southern, namely Mediterranean islands, which is the case of this study, causes differences in renewable energy potential and energy demand. Furthermore, carbon neutrality has not been chosen as the boundary condition in scenario analysis.

High heating demand accounting for almost 50% of total energy demand poses the need for different combination of technologies thus resulting in additional challenges to be solved. The categorisation techniques allow to group the islands according to the similarities thus reducing the need to choose the principal energy system design [55,59]. However, this approach may cause to overlook the need for different technological solutions and problems in the operation of specific island systems. Comprehensive analysis and scenario modelling for the subtropical climate was obtained in [10]. Sustainable transport sector was achieved through 80% share of battery electric vehicles while the remaining share included biofuel powered vehicles mainly non-private vehicles such as trucks and buses. Smart charge was applied to 50% of the electric vehicles fleet, however, the combustion power plant was still used as a backup and for emergency cases. Although, in the sustainable scenarios, the power plant is fired with biofuel, the biomass for biofuel production is not locally available but imported to the island.

With the respect to the presented literature, the lack of systematic research on the overall system modelling for a 100% sustainable energy transition on islands has been detected, especially when using only intermittent renewable energy sources and integrating the transport sector through vehicle-to-grid concept. Here, the absence of integrated modelling of the transport sector, which would include all the transport modes, i.e. personal vehicles, public transportation and marine transport stands out as one of the weakest points. Furthermore, all mentioned papers are dealing with scenario analysis, while this paper shows method which could be used for optimization and selection of wind and solar capacities in order to achieve CO_2 neutrality, i.e. to equalize island electricity import and export for a given set of boundary conditions.

Although 100% RES systems have been thoroughly analysed, authors haven't found a published research where an island system supply capacities have been optimized in order to achieve 100% CO_2 reduction and carbon neutrality, i.e. equalizing electricity import and export, while utilising V2G concept as a demand response technology with 100% share of personal and public vehicles, including a ferry line. While scenario analysis approach is commonly used for obtaining the most suited solution, this paper uses optimization procedure in order to define supply capacities by satisfying boundary condition of carbon neutrality. Optimization has been carried by running series of hourly simulations in the EnergyPLAN tool which is capable of integrating different energy sectors, including power supply, demand, storage and balancing technologies.

The objective of this paper is to complement the state-of-the art of the energy planning of 100% renewable energy systems on islands with the novelties listed below:

1. A holistic approach for energy system modelling has been taken into consideration in this paper, encompassing power, heating, cooling and transportation, including marine sector.
2. Supply capacities have been selected by using optimization, based on a series of simulations and not scenario analysis, with the boundary condition of equalizing overall electricity import and export
3. Energy production sufficient to fully meet the energy demand of the island was covered exclusively from locally intermittent renewable energy sources, while transmission line was used only in periods of insufficient local production.

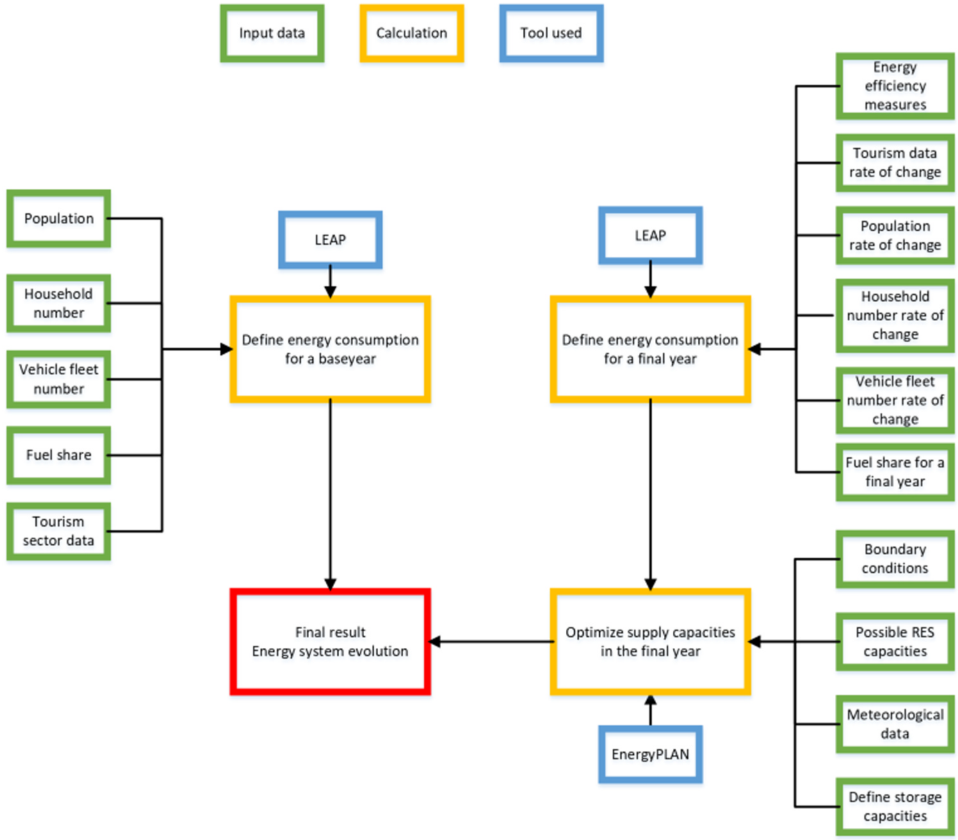

Fig. 1. General overview of the approach.

4. Impact of vehicle to grid share on overall electricity import and export, including peaks, has been shown for Mediterranean island with power supply using only intermittent renewables sources

The structure of the paper is organised as follows: Section 2 presents the method and energy system simulation tool used in this paper, while Section 3 describes the Island of Korčula as the case study used in this research. Simulation and optimization results have been displayed in Section 4, and thoroughly discussed in Section 5.

2. Method

2.1. General overview of the approach

The method used in this research could be divided in several steps, which are described in more detail in the following sections: calculating energy consumption of the reference year, defining energy consumption of the final year and finally, optimizing supply capacities for the final year with a given set of boundary conditions. The general approach is shown in Fig. 1. There are two proposed tools which could be utilized for this approach. The first one is LEAP which is used for long-term energy planning and sectoral energy consumption calculation. The second one is EnergyPLAN, with a capability of hourly simulation of an energy system for a whole year.

In the first stage, island energy system location should be defined, including the energy sectors which will be analysed. In this paper, three sectors have been taken into account: households, transport and tourism. The households sector is divided in several subsectors, transport includes only land transport, while tourism is chosen as a representative of tertiary sector since it has great impact on the overall island energy system. Different input data are needed for a base year energy system calculation since a bottom-up approach is used. Once the base year is calculated, final year goals should be defined: CO_2 emissions, RES share and energy efficiency measures including other wanted boundary conditions. Since final scenario year is in the future, the rate of change of different input data is needed, such as number of households, number of vehicles, number of overstays, etc. In the final step, supply capacities are chosen not by using scenario analysis but by using optimization based on a series of different simulations carried out in the simulation tool, in this case, EnergyPLAN. In order to optimize RES supply, related meteorological data should be known, including the maximum possible installed capacities. The optimization constraint used in this approach is that the island should be CO_2 neutral, i.e. electricity import should be equal to electricity export. Objective functions are defined as minimization of investment cost and minimization of export/import. It can be concluded from Fig. 1 that storage capacities should be defined prior to the optimization procedure.

Different steps of the proposed method are shown in detail in the following subchapters.

2.2. EnergyPLAN simulation tool

Modelling and simulation of energy systems can be done with various programmes and tools. For the purposes of this paper, EnergyPLAN has been chosen as the most suitable one. It is a free and user-friendly tool which can simulate operation of an energy system [60]. Furthermore, all energy related sectors can be modelled in detail, such as transport, heating, cooling and power sectors. EnergyPLAN was developed in 1999 at Aalborg University in Denmark, and has been continuously developed ever since. It is frequently used to study national energy systems, while energy modelling of islands and other smaller systems has also been reported. The version used in this paper is EnergyPLAN 13.2 which was released in November 2017. It contains updates which are substantial for research carried out in this paper, as explained below.

EnergyPLAN is able to simulate operation of an energy system on an hourly basis for a whole year, while taking into account different inputs defined by the end-user. In order to start a simulation, an overall energy consumption divided into several energy sectors, including supply capacities and storage size, have to be defined. Furthermore, since energy balancing of interconnected sectors is done on an hourly basis for a whole year, detailed hourly distributions such as heating, cooling and electricity demand are needed. They also have to be modelled and are treated as exogenous variable in the tool. Other input parameters such as overall technology efficiency, specific CO2 emissions or fuel cost could be used as default values or modified by the end-user. The EnergyPLAN method is based on energy and masses flow balancing between different sectors on an hourly basis for the whole year. Besides demand and supply modelling, energy balancing through different energy storages and interconnections also exists. The model is able to calculate overall running and capital costs of a system, its environmental impact in terms of CO_2 emissions, including other key performance parameters such as share of renewable energy sources in primary energy supply, etc.

In this paper, the energy system consists of heating, cooling, transport and power sectors. Power supply of the studied system is covered by using only intermittent renewable energy sources such as wind and solar, while excess and shortage of electricity is handled by electricity import and export. To increase overall stability of a system and ensure interconnection between power and transport sectors, 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. This concept is called vehicle-to-grid and is implemented in the tool. The difference between smart charging, i.e. V2G and standard dump charging can be expressed through several points, as follows. Dump charging enables vehicles only to charge their batteries. This is the equivalent to standard chargers being used for various purposes, e.g. charging phones, laptops, etc. Today, dump charging is the most frequently used method. This does not represent a problem from the technical point of view since the number of electric vehicles is still rather small. However, the strong electrification of the transport sector is expected in order to reach the EU 2050 goals, therefore requiring significant changes in the charging infrastructure. If no changes occur, the installed capacities of the power sector should be increased by a large margin. The reason for that is that the electricity requirements at times of peak demand, i.e. when citizens plug in their cars after the work, will be much higher than the existing production capacities, causing the collapse of the system. In order to prevent this, smart charging is necessary. This enables vehicles to charge from the grid, but also to discharge into the grid, depending on the conditions in the system. Therefore, the electric vehicles can act as electricity storage, increasing the stability of the system and enabling higher penetration of intermittent renewables. Energy modelling of V2G, which include personal vehicles, buses and ferries, in combination with a 100% intermittent renewable energy sources system has rarely been modelled in this detail on an hourly basis for a whole year. The updated version of EnergyPLAN could be used to regulate V2G in order to balance power plants and all electricity import and export. Driving schedule for EVs is an input parameter in a shape of hourly distribution for a period of a whole year. According to the performed literature review shown in the Introduction, a 100% intermittent renewable energy system located on an island in combination with smart charging, which includes both electrical vehicles and ferries, has never been reported to the best of authors' knowledge.

2.3. Base year energy consumption

Energy consumption of the analysed system consists of three different sectors: households, service sector and transportation. In order to model an overall energy consumption of the mentioned sectors, a bottom-up model was used, while the input data has been collected from the Energy Efficiency Action Plan of the county [61] and the Sustainable Energy Action Plan of the island [62]. Mentioned documents provide data only on fuel consumption per sector, while exact energy consumption per subsector should be additionally calculated. This has been performed by using programme called LEAP [63]. To start a simulation in the EnergyPLAN tool, besides overall energy consumption of a sector, hourly distributions are needed for heating, cooling and electricity demand. They have been created by using heating and cooling degree-hour analysis, while electricity load is acquired from the measured data provided by the grid operator. The distributions could be seen in the Annex.

In order to model overall household consumption of an island, a simple bottom-up method was used: according to the statistical data of every island's municipality, an averaged reference household was created. The main reason for this was the need to express energy consumption per household since this is the kind of input needed for the LEAP programme. Household consumption, in terms of final and useful energy, was divided in 5 subsectors: heating, cooling, domestic hot water (DHW) demand, cooking and other household appliances. Method for heating demand calculation used in this paper is presented in [64]. It is based on energy balance equations which take into account sum of transmission and ventilation losses including solar and interior gains. By using overall useful energy heating demand, final energy consumption could be calculated with the help of mean energy efficiency of the heating system. Hourly heating demand has been additionally created by using degree-hour method. Cooling demand (useful energy for cooling) is calculated in a similar manner as the heating demand. The approach presented in [64] takes into account only ventilation and transmissions gains. Again, final energy consumption could be obtained by using mean energy efficiency of the cooling system. By using the cooling degree-hour method, the hourly distribution of the cooling demand could be obtained. Domestic hot water demand is calculated by using simple mass and energy balance equations of the DHW system. By knowing the average household DHW demand in litres and average temperatures of the water system and wanted hot water, including heater efficiency, overall final energy consumption could be obtained. The calculation of useful energy for cooking is rather simple. By assuming consumption of liquefied petroleum gas (LPG), which is often used as a cooking fuel on Croatian islands, final energy demand for cooking could be obtained. The electricity consumption of other household appliances was modelled by using assumptions on average household: number of the most used electrical appliances, their nominal power and number of operating hours. Quantifying final energy consumption of a tourism sector is difficult due to its high seasonal effect. Because of that, a simplified method is proposed, which is based on scaling of the results from the county level, according to the overall number of overnights. By knowing the final energy consumption of the tourism sector in the county, final energy consumption of a tourism sector of the island could be obtained. As it has been explained, LEAP uses specific data, i.e. final energy consumption of a tourism sector has been expressed as final energy consumption per overnight stay. This is a useful approach since it is to be expected that the total number of overnights will rise in the coming decades. Fuel shares of the household and the tourism sector could be taken from different statistical data sources on county or island level. Final energy consumption of the transport sector has been calculated by using the bottom-up approach. In order to do so, specific data was gathered on the number of registered vehicles, type of the vehicle, fuel being used, as well as the data on road infrastructure of the island. Furthermore, the average consumption for each type of vehicle was used [65].

2.4. Final year energy system modelling

Once the final and useful energy consumption for the base year have been successfully acquired, the final year scenario can be modelled. The target for the final year is to achieve 100% CO_2 emissions reduction compared to the base year. By doing so, the energy system has to be also net energy independent – if it is importing electricity, the same amount has to be exported from the island. The system then becomes CO_2 neutral, since electricity produced with renewable energy sources is balanced with imported electricity which is based on fossil fuels. The entire energy demand is satisfied by using renewable energy sources – wind and solar. The heating and cooling demand, including domestic hot water production, is covered with heat pumps and solar thermal collectors. The transport sector is 100% electric, i.e. only smart and dump chargers are available on the island. Dump charge systems can only charge the vehicle's battery following their electricity demand, while smart systems schedule charging and discharging in order to reduce electricity export and import. Electrical energy storage presents the most important part of the energy system, which takes the shape of electrical batteries in households and larger batteries owned by municipalities. Car and bus batteries enable additional storage, which then increases the system flexibility and reduces the load in the transmission line between the island and the inland. Since ferries do not refuel on the island, their energy consumption has not been taken into account. In the final year, the introduction of one electrified ferry line, with a charging station on the island, was modelled. The influence of this additional capacity available for smart charging was also analysed, as shown in the Results.

2.4.1. Energy consumption

As mentioned in Section 4.2, 100% of the households were set to use heat pumps for heating and cooling. Also, thermal transmittance of walls and windows was decreased in the bottom-up model due to the expected increase of energy efficiency, i.e. building refurbishment. Since the presented method is based on the average household and the total number of households, their rate of change until the final year had to be calculated. Domestic hot water final energy consumption was mostly affected by the integration of solar thermal collectors. Energy efficiency measures regarding cooking are challenging to achieve and define. Therefore, the only difference between the base year and the final year scenario is the usage of electricity for cooking, which in this case was set to 100%. As for other household appliances, the only measure is the usage of more energy efficient devices. An increase of overnight stays on the island by the final year, which affects an overall final energy consumption of the tourism sector, was taken into account. In the final year, 100% of vehicles are electrical, with a possibility of smart charging. This is an option where electrical energy could be charged and discharged according to the current state in the grid – if there is a lack of electrical energy in the system, electrical batteries in vehicles will discharge and vice-versa. It is assumed that the total number of vehicles per household and number of buses will stay the same as in the base year.

The temporal distribution of the RES power supply is acquired using [66,67]. The method is based on the calculation of a relative power output of a wind turbine and a photovoltaic panel with regard to the meteorological data, i.e. wind speed and global solar irradiation. The hourly relative power output of supply is shown in the Annex. Besides electrical batteries in EVs, electrical energy storage also exists in the form of household batteries and power-packs owned by the municipality. It is assumed that each household has the space for 2 smaller batteries and the island municipalities have a total of 50 larger batteries, known as power-packs. Stationary battery specifications can be seen in the Annex.

In 2030, the total final energy consumption on the island will be satisfied with locally distributed intermittent renewable energy sources, wind and solar. In some periods, a need to import electricity from the inland arises. In that case it will have to export the same amount of energy in order to achieve zero net export/import condition. The sizing of the power supply system was modelled according to the overall cost and exported/imported electrical energy as shown in the following chapter.

2.4.2. Supply capacity optimization

Since the integration of wind and solar has different, i.e. an infinite number of possible solutions, the exact ratio of wind and solar capacities was defined according to the overall cost, including export and import independence. Two different boundary conditions were set: the system has to be CO_2 neutral in the final year and its cost should be as low as possible. The total cost of the supply system is defined with the overall capital investment needed to install wind and solar capacities, where the running costs of the system have been neglected. To comply with the condition of carbon neutrality, total electricity import should be the same as total electricity export. It is important to mention that the supply capacities were optimized with predefined electrical energy storage, in terms of stationary and mobile battery capacities. Furthermore, the supply system was defined for V2G share being equal to 100%. Section 4 demonstrates that the conditions of carbon neutrality and minimum capital investment cost can not be satisfied simultaneously. Due to this, two different supply capacity configurations were used to display the influence of V2G share decrease on overall electricity import and export. Furthermore, the effect of electrical ferry smart charging has been additionally studied.

In order to define the optimal combination of wind and solar capacities for the island, a set of simulations was carried out in EnergyPLAN. Each one presents a different blend of installed wind and solar power. For both technologies, 40 MW has been chosen as a maximum possible capacity. Simulations were carried out with the 2 MW step where two parameters were analysed: electricity import and export. The simulation results in the form of 3D diagrams are shown in the Section 4.

3. Case study

The island of Korčula is located in Dubrovnik – Neretva County, in the southern part of Croatia. It consists of five municipalities, with the City of Korčula being the administrative centre. Its population is 15,521 as reported in the 2011 population census and the area is 279.03 km^2, making it the 6th largest island in Croatia [62]. The climate of Korčula is typical for the Mediterranean, with the average temperature of 9.8 °C in January and 26.9 °C in July. Due to its location, it is highly suitable for the integration of renewable energy sources, particularly solar and wind. With more than 1,500 kWh/m^2 of annual global horizontal irradiation, it is one of the most insulated islands in Croatia and its number of sunny hours is the highest for the whole Adriatic region, at 2671 h. Furthermore, the southern parts of the island particularly have a significant potential for the implementation of wind power plants, with expected capacity factors above 40%. On the other hand, the geothermal potential can be practically neglected and the potential for biomass utilization is already highly exploited [62].

Currently, most of the energy sources are imported to the island. In the building sector, electricity has the highest share of final energy consumption, followed by biomass, fuel oil and LPG [62]. Out of these, only biomass can be considered as a local source, while the others are imported. Electricity is delivered by underwater cables from the mainland, while fuel oil and LPG are delivered by trucks. The transport sector is supplied by two gas stations on the island, which import gasoline and diesel by trucks. Korčula is connected to the nearby peninsula of Pelješac by a frequent ferry line and to some other cities like Dubrovnik and Split by daily ship and ferry lines.

3.1. Base year consumption

Table 1 shows total final energy consumption for the household sector, by subsectors and fuels. As expected, heating and other household appliances have the highest share in the final consumption. Final energy for cooling is only one percent of overall final energy

Table 1
Total final energy consumption and fuel share of the household's subsectors.

Subsector	Final energy consumption [GWh]	Share of a subsector
Heating	23.16	0.38
Cooling	0.57	0.01
Cooking	11.27	0.18
Domestic hot water	9.92	0.16
Other household appliances	16.57	0.27
TOTAL	61.49	1
Type of fuel	**Final energy consumption [GWh]**	**Fuel share [-]**
Electrical energy	30.81	0.5
Biomass	21.65	0.35
LPG	9.02	0.15

consumption. The reason for this could be a mismatch between the cooling demand calculated by using the cooling degree-hour method and real consumption. In addition to this, only 50% of households have air-conditioning units. Fuel shares have been taken from the existing statistical data sources on county and island level [68].

According to the acquired data and the presented method, it is possible to calculate the final energy demand for tourism sector on the island of Korčula. Overall energy consumption in the tourism sector is equal to 23.46 GWh, i.e. 29.2 kWh/overnight. Electrical energy consumption is equal to 15.25 GWh, LPG final consumption is 5.87 GWh, while the heating oil final energy consumption is equal to 2.35 GWh.

The final energy consumption for the transport sector is shown in Table 2. Diesel share in the fuel mix is equal to 55%, while gasoline holds the remaining 45%. It is important to highlight that only road transport was taken into account. The annual traveling distance of each vehicle is approximated with respect to the type of the vehicle and the length of State Road D 118, which passes through the island.

The overall final energy consumption for the base year, 2011, is shown in Table 3. Households have a total share of 39.76% and the transport sector has the highest share, around 45%.

4. Results

4.1. Final energy consumption in 2030

For the 2030 scenario, an hourly simulation was used to analyse integration of electrical vehicles into the energy system. In order to create input for the EnergyPLAN model, the calculated useful and final energy consumption has to be grouped into heating, cooling, electrical energy and transport sector demand. Table 4 presents the total demand of the island of Korčula in the year 2030.

Since one of the highest energy consumers of the island is the ferry which connects Korčula to Pelješac peninsula, converting the ferry into an electrical one was considered in this work. Electrically driven ferries have the advantage of low noise levels and no direct GHG emissions. Furthermore, they can be used for balancing of the electricity network by participating in a smart charging concept. Its battery, which usually has a capacity of more than 1 MWh, can serve as storage for renewable electricity production, while it could also supply the electricity back to the grid if needed.

This particular ferry line, which connects Dominče on Korčula with

Table 2
Final energy consumption for transport sector – by fuel type.

Final energy consumption by type fuel	Result [GWh]
Diesel – 55% share	38.22
Gasoline – 45% share	31.27
Total	69.49

Table 3
Total final energy consumption of the Island of Korčula for base year 2011.

Fuel type	Final energy consumption [GWh]
Electrical energy	46.06
Biomass	21.65
LPG	14.89
Heating oil	2.35
Diesel	38.22
Gasoline	31.27
TOTAL final consumption	154.44
Sector	**Share**
Households	39.76%
Tourism	15.17%
Transport	44.94%

Table 4
Total demand of the Island of Korčula divided in 4 groups, needed for EnergyPLAN simulation.

Electrical demand [GWh]	Heating demand [GWh]	Cooling demand [GWh]	Transport sector demand [GWh]
37.23	33.22	10.38	20,8
		Total demand	101.63 GWh

Orebić on Pelješac, docks in Dominče 14 times a day during the winter schedule and 18 times a day during summer time [69]. It is estimated that the installed power of the electrical motor is 900 kW, while the battery capacity equals to 5 MWh [70]. It is considered that the battery is mostly available during the night, when the ferry is docked on the shore of Korčula and plugged into the smart charger. However it is also charged and could be discharged during the unloading and loading of vehicles in the daytime, which presents additional significant potential.

4.2. Defining supply capacities

In order to define supply capacities, a set of simulations was carried out in EnergyPLAN, where different combinations of solar and wind capacities have been investigated. Total import and export have been analysed and presented in the 3D diagrams shown below.

Figs. 2 and 3 show electrical energy import and export as a function of installed wind and solar capacities for the energy system of Korčula in the year 2030. If there is 40 MW of installed wind in the system, then almost zero import condition can be achieved, but in that case export would be around 12 GWh. If there is 40 MW of solar, without any installed wind capacities, then import would increase to around 20 GWh, but the export would be zero.

The objective is to find a combination where import is equal to export. This solution could be obtained by subtracting electricity export from import. As displayed in Fig. 4, the obtained surface has the shape of a plane, i.e. it is again a function of two variables, installed wind and

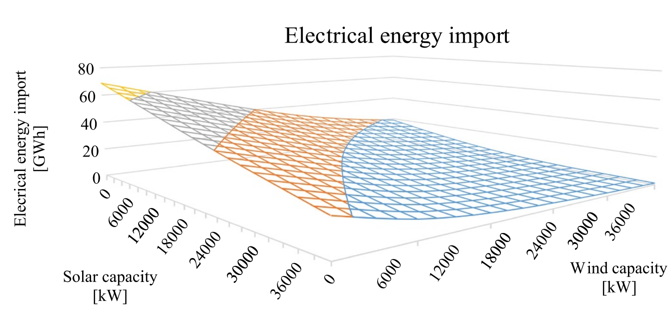

Fig. 2. Electrical energy import as a function of installed solar and wind capacity.

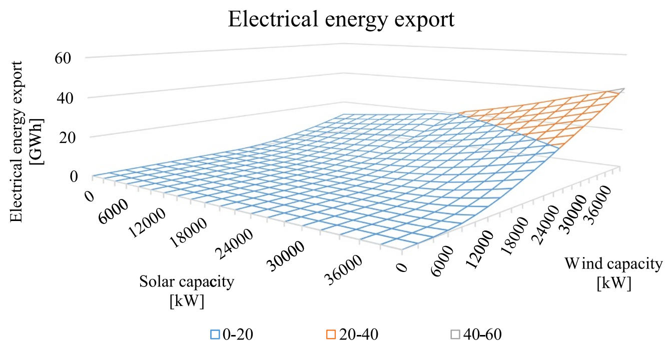

Fig. 3. Electrical energy export a function of installed solar and wind capacity.

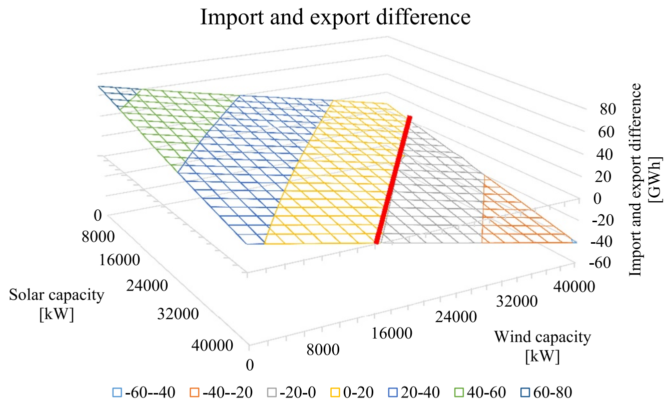

Fig. 4. Electricity import and export difference as a function of solar and wind capacity.

solar capacities. The desired combination of these technologies is the one where the resulting surface crosses the x-y plane, i.e. where z value, in this case import and export difference, is equal to zero.

In order to calculate this, equation of the plane has to be acquired through 3 chosen points. The plane equation could easily be transformed into a linear one by equalizing z with zero:

$$ax + by + cz + d = 0 \tag{1}$$

where a, b, c and d are constants, x presents solar and y wind capacity. The calculated constant values are as follows: a is equal to $-$ 1,931,200, b is $-$ 2,457,600 and finally, d is equal to $1.099 \cdot 10^{11}$. The optimal share of solar and wind capacities lay on the line marked in red in Fig. 4. The mentioned line is displayed in detail once more in Fig. 5. It shows the possible combinations of the installed capacities in order to achieve net import/export equal to zero, e.g. in order to make import and export equal, one can install 6000 kW of solar and 40,000 kW of wind, or 40,000 kW of solar and 13,300 kW of wind, etc.

In order to choose the optimal solution, total cost and total export/import has been analysed. Specific capital costs are shown in Table 5 [71,72].

Table 5
Capital and operational cost for wind turbines and solar panels.

	Wind turbine	Solar panels
Specific capital investment [€/MW]	1,550,000	1,700,000

Fig. 6 shows the total installed cost and import/export of electrical energy in relation to the installed solar capacity. If the installed solar capacity is increased from minimum (6 MW) to maximum (40 MW), the total installed cost will be raised by around 30%. The maximum total import/export of electrical energy is achieved with the minimum value of the installed solar and it is equal to 13.7 GWh. This represents a conflict of interests because the objective is to have a more independent energy system with minimum total cost. The lowest import/export of electrical energy is achieved with a combination of 30 MW of solar and 22 MW of installed wind capacities. These two cases were chosen for a more detailed analysis for V2G integration.

Although wind and solar capacities were acquired by using the optimization procedure, different additional boundary conditions should also be taken into account in order to achieve a CO_2 neutral island. These include investment limitations or socioeconomic aspects of the island's residents, such as acceptance of installing such a large number of wind turbines on the island. These limitations have not been considered in this research since local conditions sometimes cannot be easily described by using scientific methods.

4.3. V2G integration results

Integration of V2G was studied in order to analyse the impact on the total import/export of electricity in the 100% intermittent RES island system. As mentioned in Section 4.2, two combinations of power supply were studied. In addition to this, the effect of integration of smart charge was investigated. Fig. 7 shows the effect of the integration of smart charging with 30 MW of solar and 22 MW of wind installed. It can be seen that both electrical energy export and import decrease with an increased share of smart charging. This is a result of additional energy storage in the form of electrical car batteries. The effect on the maximum load of the transmission line is more visible for the export, since it is two times bigger than the import peak load. In the case of an import peak load, it even starts to rise with the smart charge integration of 40%. Fig. 8 shows similar characteristics of the energy system with 6 MW of solar and 40 MW of wind installed capacities. In both cases, export peak load is around two times higher, due to high intermittence of RES production.

Charging and discharging of electrical energy storage follows the import/export load. Fig. 9 presents the temporal distribution of charging/discharging electrical energy storage and the import/export load for the system with 30 MW of solar and 22 MW of wind. It is visible that the state of charge of the electrical energy storage is at the minimum

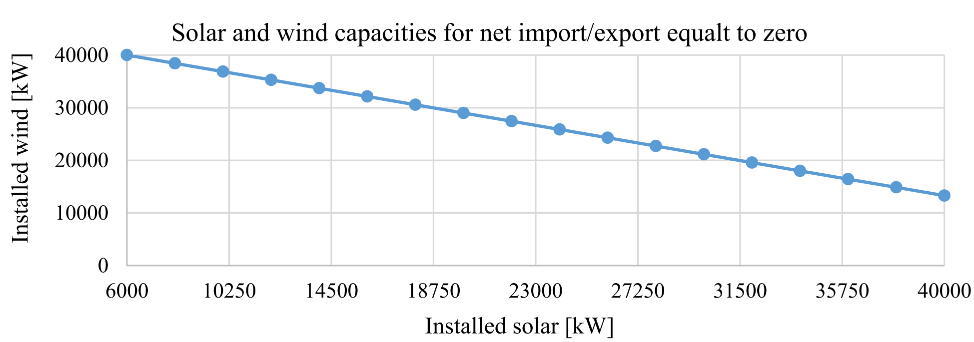

Fig. 5. Solar and wind capacities in order to achieve net import/export equal to zero.

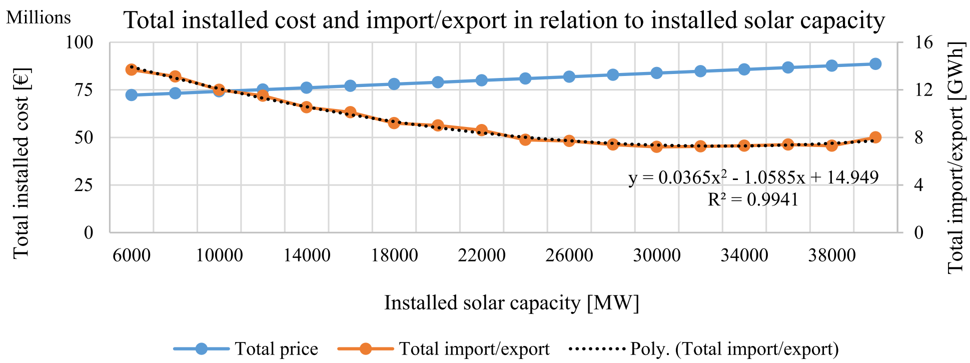

Fig. 6. Total installed cost and import/export in relation to installed power capacity.

level in the first part of the year – RES production is not enough to cover total demand of an island and additional electrical energy from the inland is needed. During the summer season, energy storage is not sufficient and electrical energy export is needed.

4.4. Energy system evolution

Fig. 10 shows the evolution of the energy system from 2011 to 2030. It is visible that import falls significantly due to the integration of RES and is finally met with the total export load. Also, in year 2030, two main objectives were reached, 100% RES share of primary energy supply (PES) and 100% CO_2 decrease, in comparison with the base year, 2011. The most important issue in the proposed method is the unavailability of energy consumption related data. For the purpose of this work, the island's SEAP from 2011 was used. This means that the energy consumption and energy system configuration shown in Fig. 10 for the year 2017, do not match real historical figures. For this reason, the presented results should be understood as a case study for the proposed method.

4.5. Socio-economic analysis

The integration of renewable energy sources can have a strong impact on local communities. In this paper, job creation was calculated, according to the IRENA data shown in [58]. It has been reported that 8.6 job-years were created for 1 MW of installed onshore wind capacity and 17.9 for 1 MW of installed PV. These jobs are linked to the manufacturing, installment and construction of the mentioned technologies. Furthermore, local permanent jobs could be created from day-to-day operations such as maintenance: 0.2 per megawatt of installed onshore wind and 0.3 per megawatt of installed PV. It is important to state that permanent jobs are more important for this analysis since they can boost the local island economy. For the scenario with optimal supply capacities of 30 MW of solar and 22 MW of wind, 726 job-years are created followed by 13.4 permanent job positions located on the island. When put into perspective with the island population, this amounts to 0.0468 job-years per citizen and 0.000865 permanent jobs per citizen.

The levelised cost of electricity (LCOE) is frequently used as a parameter for assessing economic feasibility of the proposed system or comparing different technologies, especially the ones based on renewable energy sources. In this paper, it is calculated by taking into account investment and operational costs [71,72] discounted for the technology lifetime, equal to 20 years – both for PV and onshore wind [57]. In this calculation, different aspects of the energy system, such as grid balancing or battery storage investment was not taken into account. One of the main reasons is that the grid balancing is mostly handled by V2G and battery technology which is owned by the citizens of the island. The calculated levelised cost of electricity for the scenario which involves 30 MW of PV and 22 MW of installed wind capacities is equal to 125.3 EUR/MWh.

4.6. Integration of electrical ferry

As described in the Section 3, there is a great potential for electrifying the ferry line Korčula-Pelješac. It shows how the integration of an electrical ferry line shifts the energy system of the island and its influence on electricity import and export. Ferry line Korčula-Pelješac is

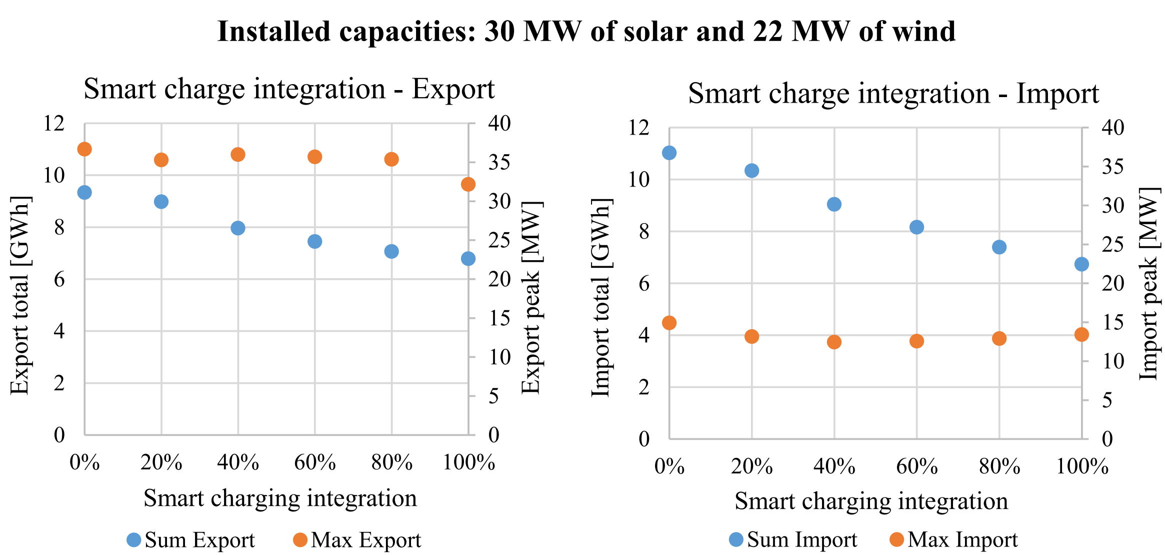

Fig. 7. Import/export characteristics for 30 MW of solar and 22 MW of wind in relation to smart charge integration.

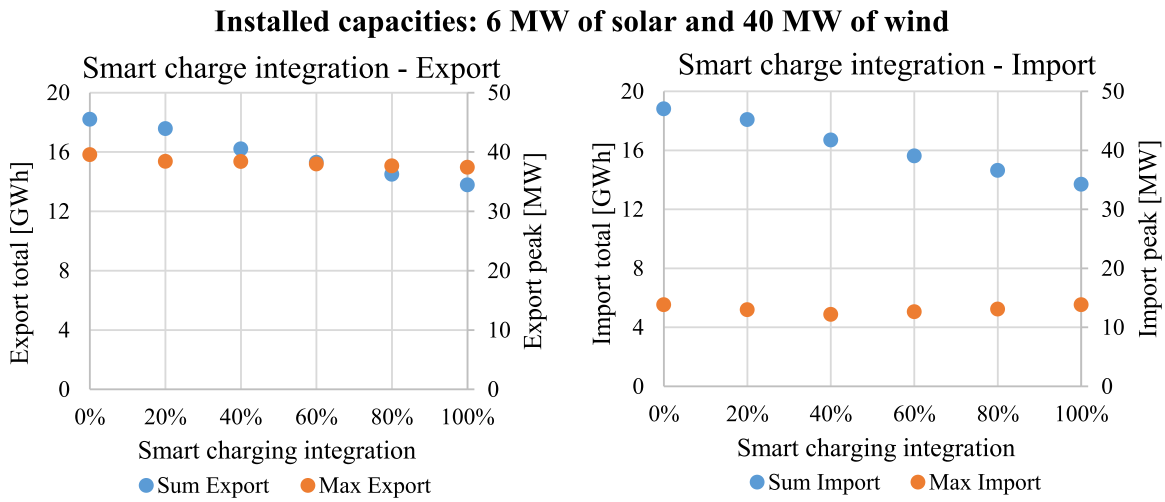

Fig. 8. Import/export characteristics for 6 MW of solar and 40 MW of wind in relation to smart charge integration.

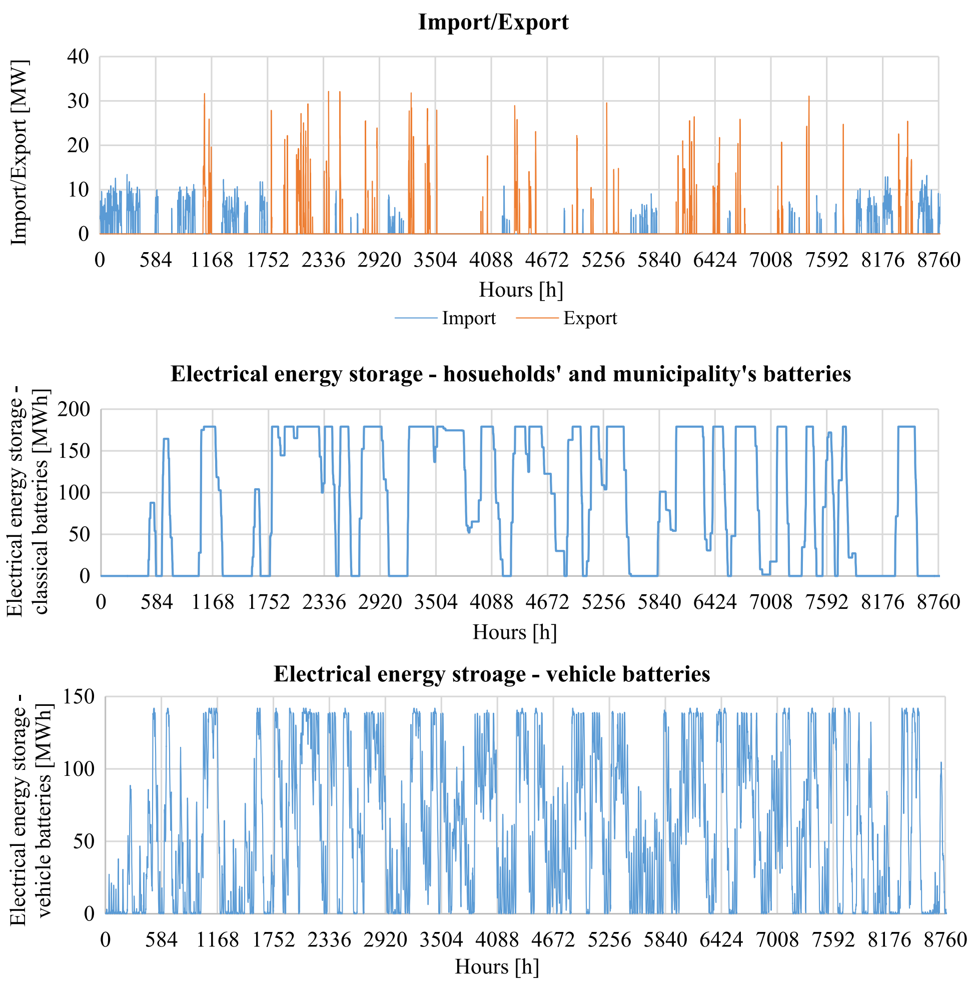

Fig. 9. Import/export load and electrical energy storage state of charge – 30 MW of solar and 22 MW of wind.

4 km long and operates every 3 h during the whole year. This small time window could be used for smart charging and additional support in electrical energy balancing between the island and the mainland. According to the existing electrical ferries, such as in Denmark [73], the proposed ferry has a 5 MWh battery and charges only on the island with the 1 MW charger unit. The overall yearly electrical energy consumption of the ferry is equal to 5.84 GWh.

Energy system simulation and analysis has also been performed by using the EnergyPLAN tool, where electrical ferries have been modelled as additional capacity to V2G. In order to model hourly distribution, the already mentioned ferry time schedule was used. The electrical ferry has been integrated into the energy system modelled for the final year, 2030, as shown in Fig. 10.

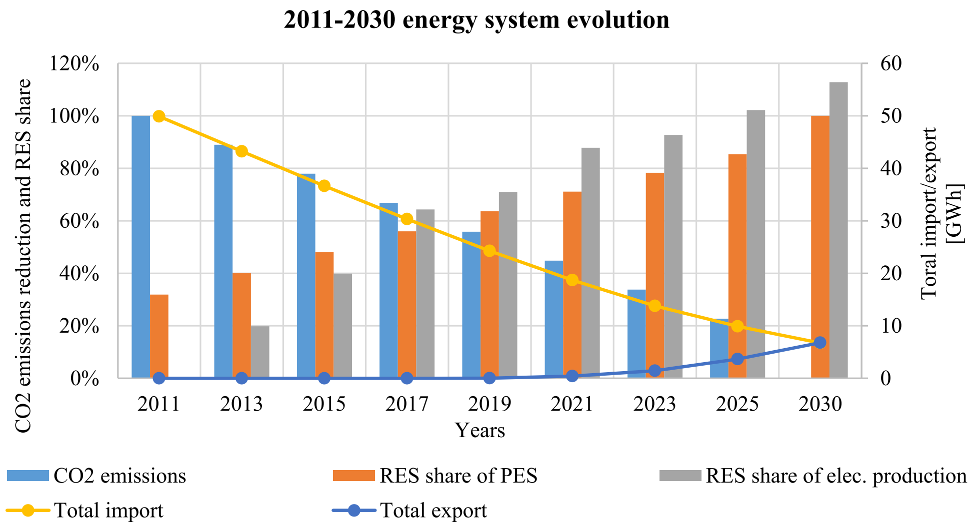

Fig. 10. 2011–2030 energy system evolution.

5. Discussion

Final energy consumption in 2030 has been decreased in every sector, while the biggest energy reduction, equal to 50 GWh, could be seen in the transport sector, as shown in Table 4. The main reason for this is the electrification of personal and public vehicles, i.e. buses on the islands. The energy consumption of marine transport has not been shown, due to the fact that ferries do not refuel on the island. The supply capacities have been selected according to the boundary conditions put on the CO_2 neutrality and the number of installed stationary and mobile batteries. Electrical energy import and export in the function of installed solar and wind capacities is shown in Figs. 2 and 3. In order to satisfy the condition of equalizing import and export, an additional plane has been displayed in Fig. 4. It shows the difference between electricity import and export, i.e. where the surface crosses the x-y plane, import is equal to zero and the CO_2 neutrality condition is satisfied. All possible combinations of solar and wind capacities for which this condition is satisfied are represented by the red line in Fig. 4. In order to acquire the equation which describes this line, constants in Eq. (1) had to be calculated. The diagram which shows possible wind and solar capacities could be seen in Fig. 5. The lowest possible installed wind capacity is equal to 13 MW, while the lowest possible solar capacity is equal to 6 MW. In order to choose the most suitable supply system configuration, two parameters have been analysed: total investment costs and the overall import, i.e. export. Fig. 6 shows the relation between installed solar capacity and total costs and electricity import/export. For every solar capacity shown in Fig. 6, wind capacity from Fig. 5 should be associated. It is apparent that the cheapest solution could be obtained for 6 MW of installed solar and 40 MW of installed wind. This configuration also has the highest import, i.e. export, which must be the same. The lowest electricity import and export is achieved for 30 MW of installed solar and 22 MW of installed wind. Since the minimum cost and the minimum import/export could not be achieved with the same configuration, these two solutions are chosen for additional analysis of V2G share reduction impact. Figs. 7 and 8 show the relation between the V2G share reduction and electricity import/export for two predefined supply system configurations. It is visible on both figures that for the 100% V2G share, total import and total export have the same values. Fig. 7 shows the V2G share reduction impact for the configuration with the lowest total import and export. If the V2G share decreases in the final year, total export would increase up to 9.5 GWh, while total import up to 11 GWh. The peak import and export loads do not change as much. The reason for this is that EnergyPLAN only minimizes the total import and export load, while peak load is not taken into account during the simulation. As can be seen in Fig. 8, which shows similar results for the supply system configuration with 6 MW of solar and 40 MW of wind, total export could be increased to 18.5 GWh and import up to 19.5 GWh if the V2G share drops to zero. Furthermore, this configuration does not show big sensitivity of the V2G share on import and export peak load. The hourly operation of electrical energy storage and the transmission grid load for 30 MW of solar and 22 MW of wind capacity is shown in Fig. 9. There is a high need for import during winter season due to the excessive use of heat pumps for heating. It could be seen that stationary batteries were depleted and mobile batteries were used for grid balancing. The opposite case is visible during the summer period where there is an excess of electricity production due to the increased production from solar and wind capacities. The evolution of the energy system which has a 100% V2G share, and an installed capacity equal to 30 MW of solar and 22 MW of wind is shown in Fig. 10. It was apparent that the boundary conditions of a 100% CO_2 reduction and equalization of import and export are satisfied. It has been shown that, once the electrical ferry is integrated in the energy system modelled for 2030, total electrical energy import increases to 9.88 GWh, while electrical energy export decreases to 4.43 GWh. Electricity import and export peak loads have not changed once the electrical ferry line was integrated.

After thorough literature review, the authors have found several papers that deal with similar detailed system analysis by taking into account only RES technologies, battery storage and V2G, including marine transport system integration. The following two are the most comparable with the result achieved in this paper: the first analyses the carbon neutral archipelago of the Canary islands [57], while the second one considers scenarios for a sustainable energy system in Finnish archipelago [58]. The first paper uses an approach similar to the one presented in this paper, since it also balances electricity import and export with the mainland. The difference is that balancing is carried out between different islands, without taking marine transportation into account. The second research paper also studies an island archipelago system, but the boundary condition of CO_2 neutrality is not taken into account. Furthermore, both studies also consider the use of biomass and cogeneration units, while this paper focuses on solar and wind capacities. Below, a detailed analysis between these studies and the obtained results is presented.

The supply configuration with the least amount of electricity import/export is 30 MW of PV in combination with 22 MW of onshore wind installed. The import/export for this configuration is equal to 6.78 GWh, which represents 130.4 MWh of electrical energy import/export for 1 MW of RES capacites installed. The results obtained in the demand response based scenario in [57] are 5.3 TWh of electrical energy import/export for 12 GW of installed supply capacities, which equals to 441 MWh electrcial energy import/export per MW of installed capacity. There are several possible reasons why this study achieves lower import/export to the installed capacity ratio. The first one is the V2G share which is set to 100% in this research, while that is not the case [57]. Instead, other different storage options are used. Furthermore, the overall import/export of the mentioned archipelago is calculated for the network between the islands, not as a connection between the mainland and the islands. Although paper [58] does not explicitly put carbon neutrality as a boundary condition, several scenarios practically achieved it. The sustainable mobility scenario which includes 100% car electrification almost achieved carbon neutrality with around 10 GWh of electricity export. The total installed capacity is 240 MW, with 125 MW of wind and 90 MW of PV. The overall V2G discharge equals to 78 GWh, which corresponds to 17.2% of overall electricity consumption. Similar result has been obtained in this research paper: 10.06 GWh of total V2G discharge which equals to 15.8% of total electricity consumption. In both cases, V2G batteries are the only way of electricity storage discharge. Different scenarios in [58], which have lower shares of V2G, have higher net electricity imports/export which was expected due to the lower demand response technology availability. This was also shown in this research, as seen in Figs. 7 and 8.

Calculated levelised cost of electricity is 125.55 EUR/MWh, which is similar to the results reported in [57], i.e. 130 EUR/MWh for demand response and RES based scenarios. The number of created jobs-years is equal to 726, i.e. 0.0468 per capita, while the number of permanent jobs is 13.4, i.e. 0.000865 per capita. Paper [58] reports 0.118121 job-years per capita and 0.001788 permanent jobs per capita. The reason for higher socioeconomic impact on the local communities is related to the total installed RES capacity in combination with different demand response technologies and lower population density.

6. Conclusion

In this paper, an analysis of an island energy system, which uses 100% intermittent renewable energy sources in combination with 100% share of smart charge vehicles, including electrical marine transportation, has been carried out. This research presents novelty since the analysis of the island system with 100% intermittent renewable energy sources has not been carried out so far. Additionally, the selection of supply capacities has not been done by implementing scenario analysis as in other conducted research but through a discrete optimization procedure, where two boundary conditions have been defined: supply capacities must include only intermittent renewable energy sources such as solar and wind, while total electricity import has to be equal to total electricity export. Objective functions have been defined as the minimization of investment costs and total electricity import, i.e. export. The approach has been tested for the case study of the Island of Korčula, Croatia. It has been shown that the same power supply configuration can not satisfy both objective functions, which means that two solutions have been selected for the smart charging share reduction analysis. In both cases, total electricity import and export has increased with the smart charge share reduction. This was expected, since other researchers have reported similar results. The import and export peak loads have not been affected by the smart charge share reduction. Once the electrical ferry line was introduced in the system configuration with 30 MW of solar and 22 MW of wind capacities, electricity export was reduced, while electricity import was increased. The reason for this is the high share of the electrical ferry in the energy demand of the transport sector. The electrification of marine transport with smart charge integration could be a viable option for larger energy systems where this sector does not have such a large share in the overall energy consumption.

The approach of optimizing carbon-neutral energy system of the island which integrates different energy sectors, 100% intermittent RES capacities and 100% share of V2G used as demand response technologies, including marine transportation, could be significantly improved. Different important aspects of energy system such as storage capacity and the V2G share could also be optimized. This could highly impact the overall costs and electricity import, i.e. export, thus shifting the supply configuration solution. Furthermore, the multi-objective optimization approach could be integrated in order to analyse additional different objective functions, such as CO_2 emissions. The minimization of total investment costs and the minimization of greenhouse gas emissions often results in a conflict of interest, thus Pareto optimality could be considered. In terms of constraints, boundary conditions, such as the local market or economic feasibility limitations, could be added in the model. This could enable the achievement of more realistic results from the perspective of local investors and their financial possibilities. Finally, life-cycle analysis in combination with long-term supply capacity installation planning could also be integrated.

Acknowledgements

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Annex

Base year consumption input data

In order to calculate energy demand for the household sector, additional statistical data is needed. Table A1 shows the statistical data per municipality. (Table A2).

Data needed to calculate final energy consumption of the tourism sector on the Island of Korčula is shown in Table A3. Fuel share of Korčula is assumed to be the same as on the Dubrovnik-Neretva County level. (Table A4)

Table A1
Statistical data needed for calculation of energy consumption of household sector.

Input data	County				
	Vela Luka	Blato	Smokvica	Korčula	Lumbarda
n_{people} [-]	4,137	3,593	918	5,663	1,213
$n_{households}$ [-]	1,503	1,165	357	2,011	413
$A_{municipality}$ [m^2]	133,895	103,287	33,706	164,700	36,161
$A_{household}$ [m^2]	89.1	88.7	94.4	81.9	87.6
n_{rooms} [-]	5,195	3,877	1.278	2,011	1,283
$n_{rooms,\ household}$ [-]	3.5	3.3	3.6	3.2	3.1
$n_{split-system}$ [-]	853	643	188	1,083	213

Table A2
Data needed for calculation of the energy consumption of the household sector.

Input data	Unit	Value
h	–	0.8
U_v	W/m^2 K	1.2
$T_{outside}$	°C	Set of values [56]
T_{inside}	°C	21
U_w	W/m^2 K	3.5
ρ_{air}	kg/m^3	1.2
$c_{p,air}$	kJ/kgK	1.005
h_e	m	2.2
$n_{exchange}$	h^{-1}	2
g	–	0.53
a_f	–	0.96
ps	–	0.8
I	W/m^2	Set of values [56]
q_{spec}	W/m^2	5.5 [57]
V_{DHW}	L/day/person	50
ϑ_{DHW}	°C	45
ϑ_{heater}	°C	55
$\vartheta_{water\ system}$	°C	18
n_{LPG}	tanks/month	1.3
m_{LPG}	kg	10
$H_{l,LPG}$	kWh/kg	12.87

Table A3
Data input needed for final demand calculation of a tourism sector.

Input data	Value
$n_{nights,island}$ [-]	811,579
$n_{nights,county}$ [-]	4,900,000
$E_{tourism,county}$ [GWh]	141.7
Share of electrical energy [44]	0.65
Share of LPG [44]	0.25
Share of heating oil [44]	0.1

Table A4
Data input for transport sector final energy consumption calculation.

Type of vehicle	*i*	Average consumption (L/100 km)	Annual traveling distance (km)
Personal vehicle - gasoline	1	7.61	10,000
Personal vehicle - diesel	2	5.95	10,000
Mopeds	3	5.01	1,000
Motorcycles	4	7.03	5,000
Bus	5	30.12	10,000
Heavy duty vehicles	6	30.12	10,000
Combined vehicles	7	11.21	10,000
Tractor	8	25.07	500
Quad motorcycles	9	6.11	1,000
Vehicle type		Number of vehicles in 2011	
Gasoline vehicles		1,689	
Diesel vehicles		3,941	
Total number of vehicles		5,630	

Table A5
Total number of households in the year 2030, per counties.

	Vela Luka	Blato	Smokvica	Korčula	Lumbarda
Annual change	− 0.38%	0.5%	0.82%	0.48%	0.98%
Total number in 2030	1296	1,415	491	2,424	604

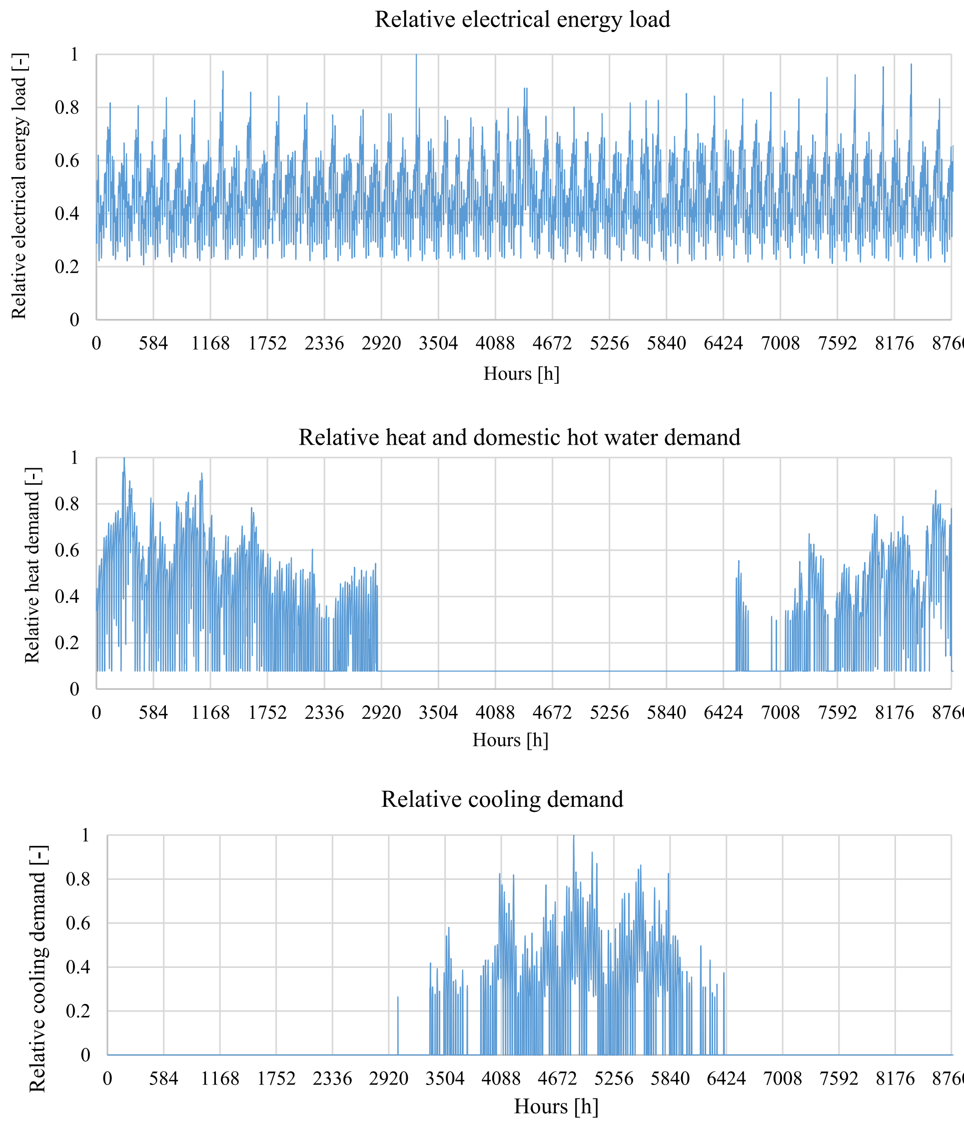

Fig. A1. Relative electrical energy, heating and cooling demand.

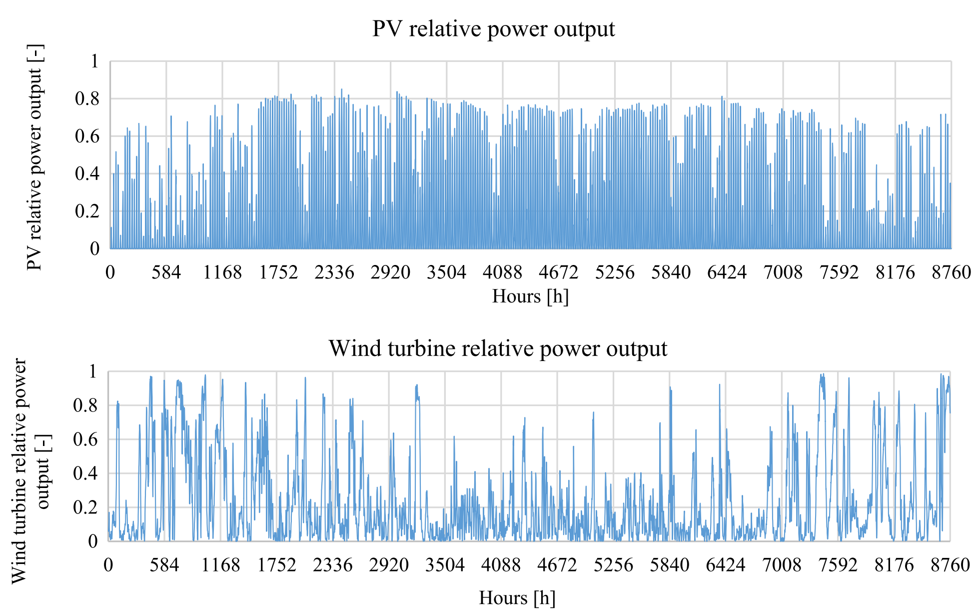

Fig. A2. Relative power output of renewable energy sources.

Table A6
Total overnights on the Island of Korčula per Municipality, year 2030.

	Vela Luka	Blato	Smokvica	Korčula	Lumbarda
$n_{nights,municipality}$	277,200	272,600	91,600	647,700	277,200

Table A7
input data needed for 2030 scenario calculation.

Overall kilometres travelled	Specific energy consumption, gasoline engine	Specific energy consumption, diesel engine	Specific energy consumption, electrical engine	Charging and discharging power	Battery capacity
104,000,000 km/year	1.5 km/kWh	1.3 km/kWh	5 km/kWh	11 kW	22 kWh

Table A8
Batteries characteristics used in final year scenario.

Smaller battery capacity	**Smaller (household) battery charging/ discharging power**	**Bigger (municipality) battery capacity**	**Bigger battery charging/ discharging power**
13.5 kWh	5 kW	210 kWh	50 kW

Final year scenario input data

In order to calculate the consumption of the average household for the energy efficient 2030 scenario, energy renovation measures will have to be defined. It is assumed that the thermal transmittance of walls (U_v) and windows (U_w) of an average household will have the following values: 0.8 and 2.5 W/m^2 K. According to the extrapolation of the data from [74], the total number of households in 2030 is shown in Table A5.

Electrical energy demand distribution is acquired by using the islands' transformer station. As explained in Section 2, the heating and cooling demand distribution is calculated by using degree-hour analysis. Hourly distributions of relative electrical energy demand, heating and cooling are shown in Fig. A1. Hourly realtive power output of renewable energy sources, solar and wind is shown in Fig. A2.

In order to calculate the total number of overnights in 2030, data from [75] has been extrapolated as shown in Table A6.

Transport sector input data – 2030 scenario

As explained in Section 2, the overall number of vehicles per household will stay the same as in the base year. Final energy consumption for year 2030 is calculated by using the overall travelled distance in year 2011 and specific final energy fuel consumption per engine type. An additional assumption is that the overall travelled distance in 2030 will stay the same as in year 2011. Also, charging/discharging peak power and battery capacity have also been assumed for year 2030. All the required input is shown in Table A7. (Table A8).

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