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

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Abstract

Islands' energy systems present challenge in energy planning due to the limited amount of resources which could be used to make island self-sufficient and sustainable. Current energy policy of the most islands is based on import of fossil fuels and electricity from the mainland, while locally available renewable energy sources potential is still left unfulfilled. This paper presents novel approach where energy system of an island is based on usage of only intermittent renewable energy sources in combination with electrical storage in the shape of stationary and mobile batteries. Integration of power, heating, cooling and transport sector has been modelled by using EnergyPLAN tool, i.e. its updated November 2017 version which is capable of simulating vehicle-to-grid operation in these conditions. Power supply capacities have been selected not by using scenario analysis but simple optimization procedure based on serial simulation in the EnergyPLAN tool. In order to select most suitable power supply system configuration, two boundary conditions have been defined: only solar and wind capacities should be utilized, while total electricity import and export should be balanced, i.e. the island should be CO_2 neutral. In order to validate the approach, Croatian Island of Korčula has been used as the case study. It has been shown that configuration with 40 MW wind and 6 MW of solar present the least cost solution, while 22 MW in combination with 30 MW of wind provide the lowest amount of total electricity import and export. Analysis of vehicle-to-grid share reduction has shown increase of total import and export in both cases, while transmission peak loads haven't been influenced by this reduction. Furthermore, integration of electrified marine transport through single ferry line which connect island with the mainland has shown to increase total import and decrease total export, while the transmission peak loads haven't been influenced.

Keywords: energy planning; renewable energy sources; islands; batteries; vehicle-to-grid; EnergyPLAN

1. Introduction

Significant problem of island communities has traditionally been energy import and transport of fuel supply. Introducing renewable energy sources (RES) and integrating energy demand of domestic heating, cooling, fuels for transport or larger, commercial demand is becoming one of the most investigated ways of making local island communities more energy self-sufficient.

On the one hand island poses a significantly unexploited potential for sustainable development while on the other they are among the most vulnerable areas to experience adverse impacts of climate change on their local ecosystem and livelihoods. This has been recognised and acknowledged through several initiatives targeting sustainable development on islands. 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 the 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 bottom-up initiative tackling climate change and supporting sustainable economic growth through holistic approach by exploiting synergies between sectors thus directly addressing circular economy. Initiatives seek to gather European islands by developing a common method for the clean energy transition focusing on smart islands principles.

In renewable energy planning various options of resource and technology combinations can be applied on islands resulting in different technical and economical feasibilities. N. Duić et al. [5] developed the RenewIsland methodology specially designed to enable assessment of alternative scenarios for energy and resource planning. The methodology supports renewable energy scenarios design through systematic and comprehensive approach divided in 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 computer tool called H2RES designed as a support for the island energy system modelling with the RenewIsland methodology [6], [7], [8]. H2RES was used in [7] to show how the integration of desalination plant can support higher penetration of renewable energy sources reaching up to 72% renewable energy source production in year 2020. Apart from using tools especially 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 number of case studies, i.e. La Gomera (Spain) [9], Thai island Wang-an (Taiwan) [10], Vis, Lastovo, Korcula [11], Mljet [11], [12] and Hvar [13] (Croatia) while the HOMER tool developed for local community and single project energy systems has been applied on island system such as for Agios Efstratios (Greece) [14], St. Martin (Bangladesh) [15], Prince Edward (Canada) [16] and Vis (Croatia) island [17].

Modelling renewable energy systems for self-sufficient islands requires special attention placed on the balancing of the renewable energy generation. Different energy systems have been designed in order to balance 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 [18], [19], [20]. High share of renewable energy sources can be achieved with utilising typical energy storage technologies such as batteries and hydro storage. Cost benefit analysis of a photovoltaic generators and appropriate energy storage solution, namely batteries or hydro storage was analysed for 33 Aegean islands (Greece) of different sizes [21]. Both storage technologies were also evaluated in [22] and [23] for remote island in Hong Kong. Furthermore, integration of hydrogen as a balancing option for the island energy transition was analysed in [24]. Moreover, coupling of different sectors represents successful approach to enable high levels of variable renewable energy sources [25]. Such integration can best be achieved through a smart energy system which enables to detect and utilize synergies between different sectors [26]. Smart energy systems thus provide better management of variable renewable energy generation as well as their higher penetration. The polygeneration system, combining electricity and water supply systems, as well as heating and cooling supply was investigated on the case study of Pantalleria island (Italy) [27]. The research showed that polygeneration approach can fulfil the water demand of the community and supply significant amounts of electricity, heating and cooling energy. The importance of RES integration and storage technologies, together with energy savings and improvements in energy efficiency in the energy production was highlighted in the case of an island of Hvar (Croatia) [13]. Integration of various sectors and energy types can often be observed in modelling of 100% renewable energy system as for the achievement of such systems all 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 [10], [14], [16], [28], [29]. A feasibility study for replacement of diesel-generators with renewable energy technologies for the case of small Greek island was carried out in [14]. Due to the extreme seasonal variations in energy consumption caused by tourism industry, D. Thomas et al. envisaged enormous capacity of solar and wind as well as battery storage in for the case of nearly 100% renewable energy system. Moreover, they highlighted potential technical difficulties of nearly 100%, namely maintaining stable voltage and frequency in the grid. N. Maïzi et al. [28] 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 in the case of Reunion island (France, Indian Ocean) [29] 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 [10] showing that 100% renewable electricity can be achieved through deployment of storages. Storage technology was envisaged, on the one hand to maintain 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 [30]. The obtained analysis aimed to provide results for fostering development of 100% renewable energy island systems. A. Khoodaruth et al. [31] analysed present and proposed energy strategies for Mauritius and went 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 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 technologies and 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.

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 [32]. D. F. Dominković et al. [33] analysed four main solutions for the replacement of the fossil fuel, i.e. biofuels, hydrogen and synthetic fuels (electrofuels). The review pointed out that 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 [34]. 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 [35] 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 of all buses were electric where China had the leading role with over 8.3 percent of the global total. It has also been pointed out in [33] that there is a quite 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 [36], [37], [38]. 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 [39]. 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. [11] 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 [40]. 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 [41]. 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. 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 [39], [42]. 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 [9]. 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, it has been detected the lack of systematic research on overall system modelling for the 100% sustainable energy transition on islands, especially by using only intermittent renewable energy sources and transport sector. Here, the absence of integrated modelling of the transport sector which would include all transport modes, 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 import and export for a given set of boundary conditions.

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 following novelties:

1. A holistic approach for energy system modelling has been taken into consideration in this paper, encompassing power, heating, cooling and transportation sector.
2. A special attention was placed on the transport sector modelling including following transport modes: personal vehicles, public transportation and marine transport.
3. Smart charging is applied to all electrified vehicles to fully utilize the potential of vehicle's batteries in balancing variable renewable electricity generation with the electricity demand.
4. Supply capacities have been selected by using optimization, not scenario analysis, so the boundary condition of equalizing overall electricity import and export has been achieved
5. Energy production sufficient to fully meet energy demand of the islands was covered exclusively from locally intermittent renewable energy sources, while transmission line was used only in periods of insufficient local production.
6. Impact of vehicle to grid share on overall electricity import and export, including peaks, has been shown for 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 describe 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. 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 suited one. It is free and user friendly tool which can simulate operation of energy system [43]. Furthermore, all energy related sectors can be modelled in detail, such as transport, heating, cooling and power sector. EnergyPLAN was developed in 1999 in Aalborg University in Denmark, and is continuously developed ever since. It is 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 update which are substantial for research carried out in this paper, as explained below.

EnergyPLAN is tool able to simulate operation of an energy system on hourly level for a whole year, while taking into account different inputs defined by the end-user. In order to start the simulation, overall energy consumption divided in several energy sectors, supply capacities and storage size have to be defined. Furthermore, since energy balancing of interconnected sectors is done on hourly level 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. EnergyPLAN method is based on energy and masses flow balancing between different sectors on hourly level for a whole year. Besides demand and supply modelling, energy balancing through different energy storages and interconnection also exists. The model is able to calculate overall running and capital costs of the system, its environmental impact in terms of CO2 emissions, including other key performance parameters such as share of renewable energy sources in primary energy supply, etc.

In this paper, 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 the 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 minimize production from conventional power plants. This concept is called vehicle-to-grid and is implemented in the tool. Energy modelling of V2G, which include personal vehicles, busses and ferries, in combination with 100% intermittent renewable energy sources system has never been modelled on the hourly level for a whole year. Updated version of EnergyPLAN could be used to regulate V2G in order to balance power plants and all electricity import and export. According to the performed literature review shown in Introduction, 100% intermittent renewable energy system in combination with smart charging, which include both electrical vehicles and ferries, has never been reported.

2.2. Base year energy consumption

Energy consumption of the analysed system consists of three different sectors: households, service sector and transportation. In order to model overall energy consumption of mentioned sectors, bottom-up model was used, while the input data has been collected from Energy efficiency action plan of the county [44] and Sustainable Energy Action Plan of an island [45]. Mentioned documents only provide data only on fuel consumption per sector, while exact energy consumption per subsector should be additionally calculated. Calculation has been performed by using programme called LEAP [46]. To start a simulation in the EnergyPLAN tool, besides overall energy consumption of the 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 measured data provided by the grid operator. The distributions could be seen in the Annex.

In order to model the overall household consumption of the island a simple bottom-up method was used: according to the statistical data of every island's municipality, the averaged reference household was created. The main reason for this was the need to express energy consumption per household since this is kind of an input needed for LEAP programme. Household consumption, in terms of final and useful energy, was divided in 5 categories: heating, cooling, domestic hot water demand, cooking and other household appliances. Method for heating demand calculation used in this paper is presented in [47]. It is based on energy balance equations which take into account sums of transmission and ventilation losses including solar and interior gains. By using overall useful energy heating demand, final energy consumption could be calculated by using mean energy efficiency of a 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. Approach presented in [47] 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 cooling degree-hour method, hourly distribution of the cooling demand could be obtained. Domestic hot water (DHW) demand is calculated by using simple mass and energy balance equations of the DHW system. By knowing average household DHW demand in litres and average temperatures of the water system and a wanted hot water, including heater efficiency, overall final energy consumption could be obtained. 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. Electricity consumption of other household appliances was modelled by using assumptions on average household on the island: number of most used electrical appliances, their nominal power and number of hours which they operate. Quantifying final energy consumption of a tourism sector is difficult due to its high seasonal effect. Because of that, a simple method is proposed, which is based on scaling of the results from the county level, according to the overall number of overnights. By knowing an overall tourism sector final energy consumption of 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 will be expressed as a final energy consumption per overnight stay. This is useful approach since it is to expect that total number of overnights will rise in the coming decades. Final energy consumption of the transport sector has been calculated using the bottom-up approach. In order to do so, specific data has to be 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. Data was provided by The Croatian Ministry of Internal Affairs. Furthermore, average consumption for each type of vehicle has been used [48].

2.3. Final year energy system modelling

Once the final and useful energy consumption for the base year was successfully acquired, a final year scenario can be modelled. 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 also based on fossil fuels. The whole energy demand is satisfied by using renewable energy sources – wind and solar. Heating and cooling demand, including domestic hot water production is covered with heat pumps and solar thermal collectors. 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 present the most important part of the energy system, which takes 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 reduce the load in the transmission line between the island and the inland. Since ferries don't refuel on the island, their energy consumption hasn't been taken into account. In the final year, introduction of one electrified ferry line, with charging station on the island, has been modelled. The influence of this additional capacity available for smart charging was also analysed, as shown in Results.

2.3.1. Energy consumption

As mentioned in chapter Final year energy system modelling, 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. Since presented method is based on the average household and a total number of households, it was needed to calculate their rate of change by the final year. Domestic hot water final energy consumption was mostly affected by 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 a final year scenario is usage of electricity for cooking, which in this case is equal to 100%. As for other household appliances, the only measure is 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 the vehicles is 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 total number of vehicles per household and number of busses will stay the same as in the base year.

Temporal distribution of RES power supply is acquired using [49] and [50]. Relative power output of supply is shown in Annex. Besides electrical batteries in EVs, electrical energy storage also exists in a shape of households' batteries and power-packs owned by municipality. It is assumed that each household has space for 2 smaller batteries and island's municipalities have total of 50 larger batteries, known as power-packs. Stationary battery specifications can be seen in Annex.

In the final year, a whole final energy consumption on the island will be satisfied with locally distributed renewable energy sources, wind and solar. In some periods, there is need to import electricity from the inland. In that case it will have to export the same amount of energy in order to achieve zero net export/import condition. Sizing of the power supply system was modelled according to the overall cost and exported/imported electrical energy.

2.3.2. Supply capacity optimization

Since the integration of wind and solar has different possible solutions, exact ratio of wind and solar capacities was defined according to the overall cost and export and import independence. Two different boundary conditions were set: the system has to be CO_2 neutral in the final year and it should cost as least as possible. The total cost of the supply system is defined with overall capital investment needed to install wind and solar capacities, where running costs of the system have been neglected. To satisfy condition of carbon neutrality, total electricity import should be the same as total electricity export. It is important to mention that supply capacities were optimized with predefined electrical energy storage, in terms of stationary and mobile battery capacities. Furthermore, supply system was defined for V2G share equal to 100%. It was shown in Results that conditions of carbon neutrality and minimum capital investment cost can't be satisfied simultaneously. Due to this, two different supply capacity combinations were used to display 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 optimal combination of wind and solar capacities for the island, set of simulations was carried out in EnergyPLAN. Each one presents 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 2 MW step where two parameters were analysed: electricity import and export. The simulation results, in a shape of 3D diagrams are shown in Results.

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 center. Its population is 15,521 as reported in the 2011 population census and the area is 279.03 km^2, making it the 6^{th} largest island in Croatia [45].The climate of Korčula is typical 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 1500 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 2,671 h. Furthermore, especially southern parts of the island have a significant potential for the implementation of wind power plants, with expected capacity factors above 40%. On the other hand, geothermal potential can be practically neglected and the potential for biomass utilization is already highly exploited [45].

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 [45]. Out of these, only biomass can be considered as a local source, while the others are imported. Electricity is delivered by the underwater cables from the mainland, while fuel oil and LPG are delivered by trucks. 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 household sector, by subsectors and fuels. As expected, heating and other household appliances have the biggest share in the final consumption. Final energy for is only one percent of overall final energy consumption. The reason for this could be a mismatch between calculated cooling demand by using cooling degree-hour method and real consumption. In addition to this, only 50% of households have air-conditioning units.

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	21.85	0.35
LPG	9.02	0.15

According to the acquired data and presented method, it is possible to calculate final energy demand for tourism sector for the island of Korčula. Overall energy consumption in 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 heating oil final energy consumption is equal to 2.35 GWh.

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 the State Road D 118, which passes through the island.

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

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

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 %

4. Results

4.1. Final energy consumption in 2030

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

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

Since one of the highest energy consumers of the island is the ferry which connects Korčula to Pelješac peninsula, this work considered switching it to an electrical one. Electrically driven ferries have the advantage of low noise levels, and no direct GHG emissions. Furthermore, they can be used for the balancing of the electricity network by participating in the smart charging concept. Its battery, which usually has a capacity of more than 1 MWh, can serve as a storage for the 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 Orebić in Pelješac, docks in Dominče 14 times a day during the winter schedule and 18 times a day during summer time [51]. It is estimated that the installed power of the electrical motor is 900 kW, while the battery capacity equals to 5 MWh [52]. It is considered that the battery is mostly available during the night, when the ferry is docked on the shore of Korčula and plugged in to 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, set of simulations was carried out in the EnergyPLAN, where different combinations of solar and wind capacities have been investigated. Total import and export have been analysed and presented in 3D diagrams shown below.

Figure 2 and Figure 5 show electrical energy import and export as a function of installed wind and solar capacities for an 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 decrease to around 20 GWh, but the export would be zero.

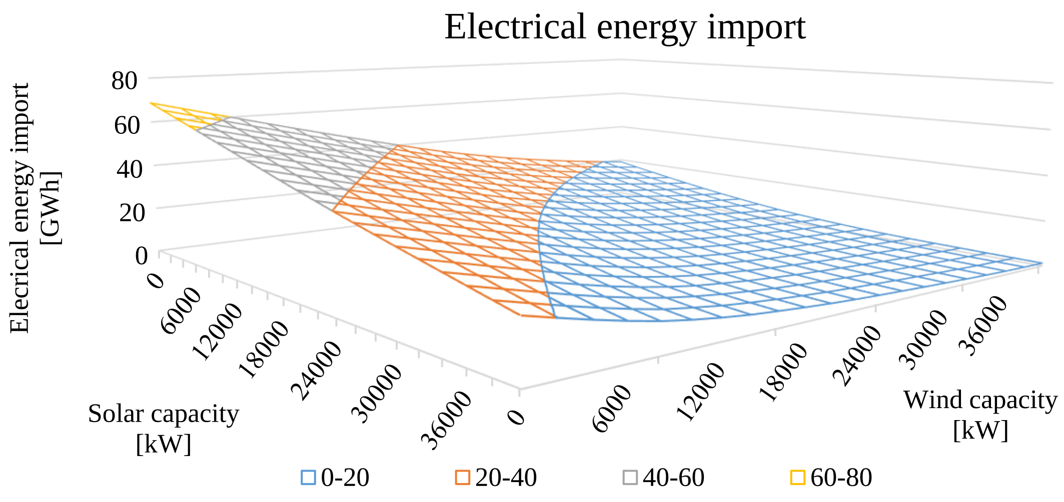

Figure 1 Electrical energy import as a function of installed solar and wind capacity

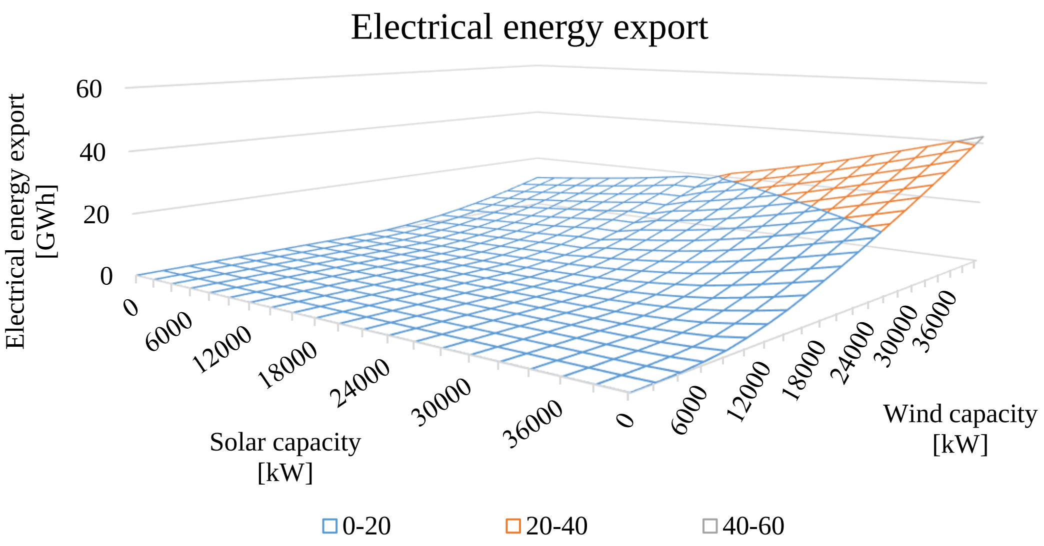

Figure 2 Electrical energy export a function of installed solar and wind capacity

The objective is to find a combination where import is equal to export. This surface could be obtained by subtracting electricity import and export. As displayed in Figure 3, the surface has shape of a plane. Wanted combination of solar and wind capacities is the one where resulted surface crosses the x-y plane, i.e. where z value (import and export difference) is equal to zero.

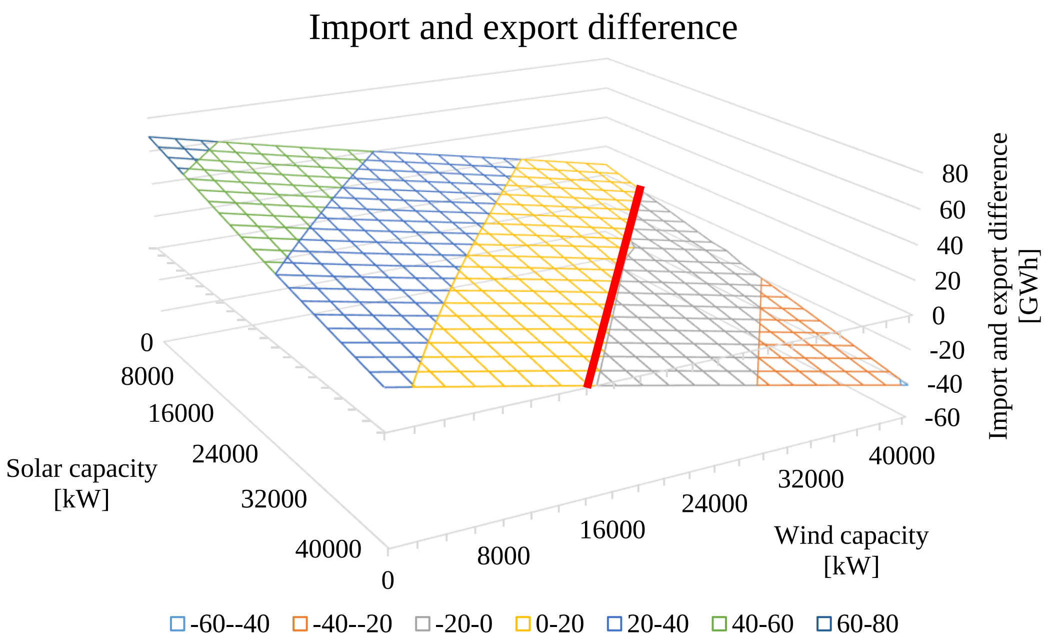

Figure 3 Electricity import and export difference as a function of solar and wind capacity

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

$$ax + by + cz + d = 0 \quad (1)$$

Where a, b, c and d are constants, x presents solar and y wind capacity. Constant a is calculated to be 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 as red in Figure 3. Mentioned line is displayed in detail in Figure

4. It shows the possible combinations of 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 6,000 kW of solar and 40,000 kW of wind, or 40,000 kW of solar and 13,300 kW of wind, etc.

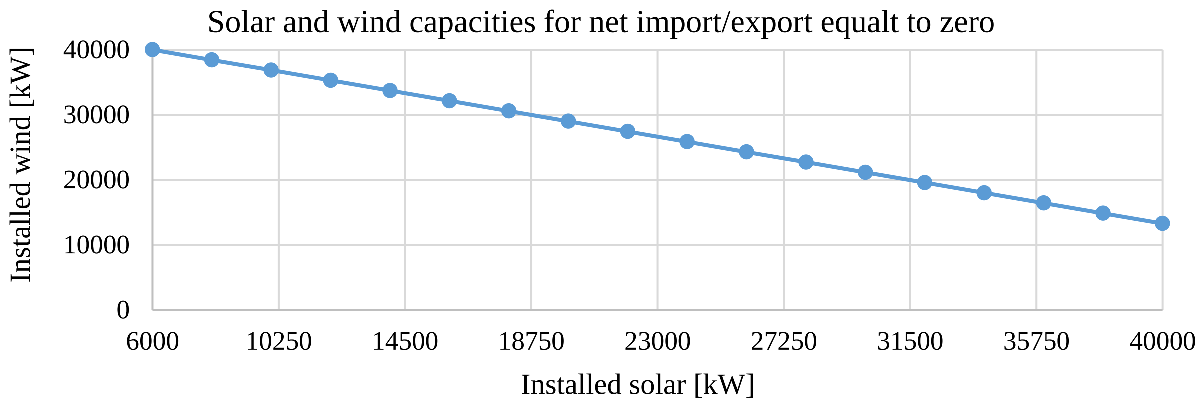

Figure 4 Solar and wind capacities in order to achieve net import/export equal to zero

In order to choose optimal solution, total cost and total export/import will be analysed. Specific capital cost are shown in Table 5 [53], [54].

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

Figure 5 shows the total cost and import/export of electrical energy in relation to 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%. Maximum total import/export of electrical energy is achieved with minimum value of 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 combination of 30 MW of solar and 22 MW of installed wind capacities. These two cases were analysed for V2G integration.

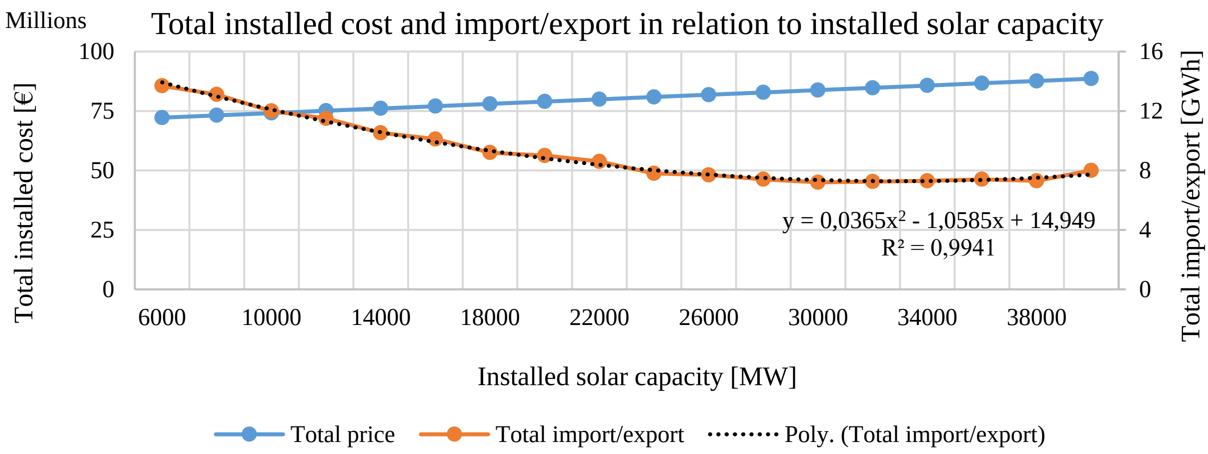

Figure 5 Total installed cost and import/export in relation to installed power capacity

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% RES system. As mentioned in chapter Defining supply capacities**s**Defining supply capacitie***s***, two combinations of power supply were studied. In addition to this, the effect of integration of smart charge was investigated. Figure 6 shows the effect of 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 increased share of smart charging. This is the result of an additional energy storage in a form of electrical car batteries. The effect on a maximum load of transmission line is more visible for the export, since it is twice bigger than the import peak load. In a case of an import peak load, it even starts to rise with the smart charge integration of 40%. Figure 7 shows similar characteristics with energy system with 6 MW of solar and 40 MW of wind installed capacities. In both cases, export peak load is around 2 times higher, due to high intermittence of RES production.

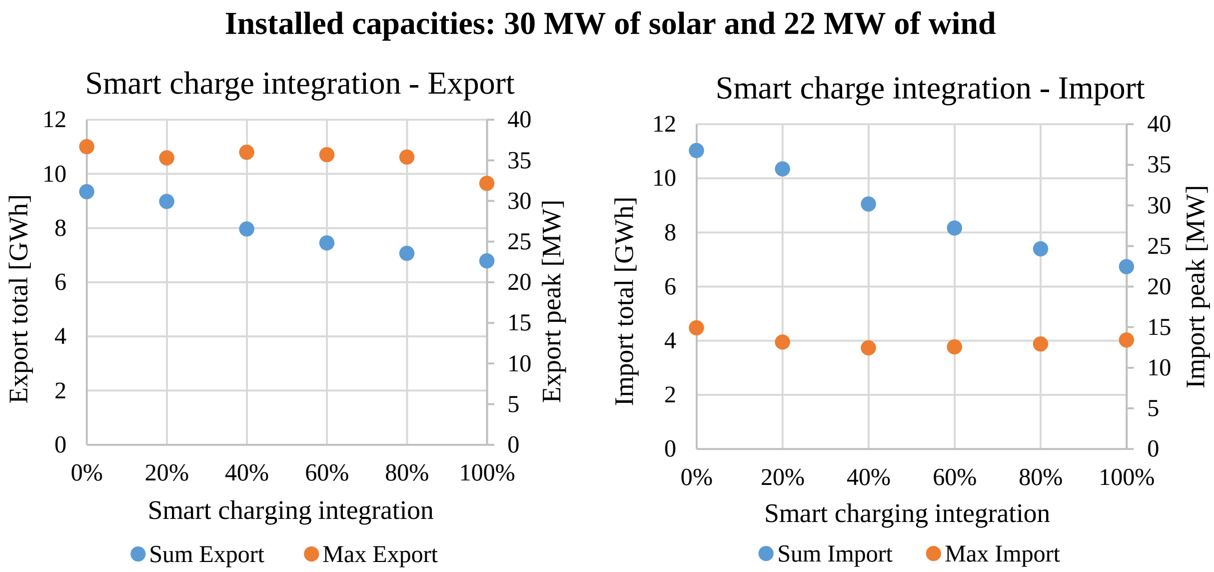

Figure 6 Import/export characteristics for 30 MW of solar and 22 MW of wind in relation to smart charge integration

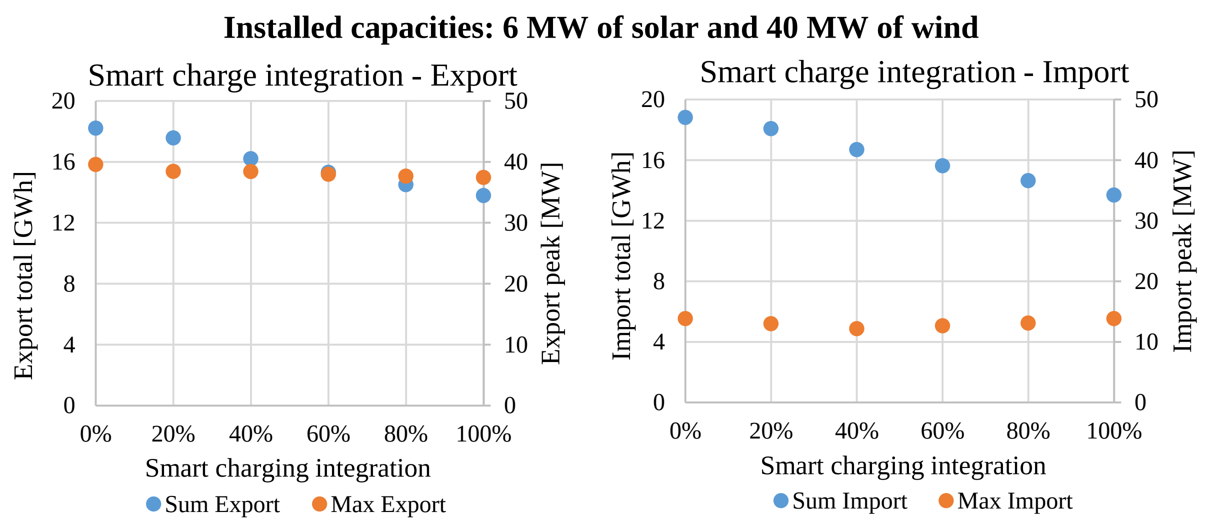

Figure 7 Import/export characteristics for 6 MW of solar and 40 MW of wind in relation to smart charge integration

Charging and discharging of an electrical energy storage follows import/export load. Figure 8 presents temporal distribution of charging/discharging of electrical energy storage and import/export load for the system with 30 MW of solar and 22 MW of wind. It is visible that state of charge of the electrical energy storage is at minimum level in the first part of the year – RES production isn't enough to cover total demand of an island and additional electrical energy from the inland is needed. During summer season, energy storage isn't sufficient and electrical energy export is needed.

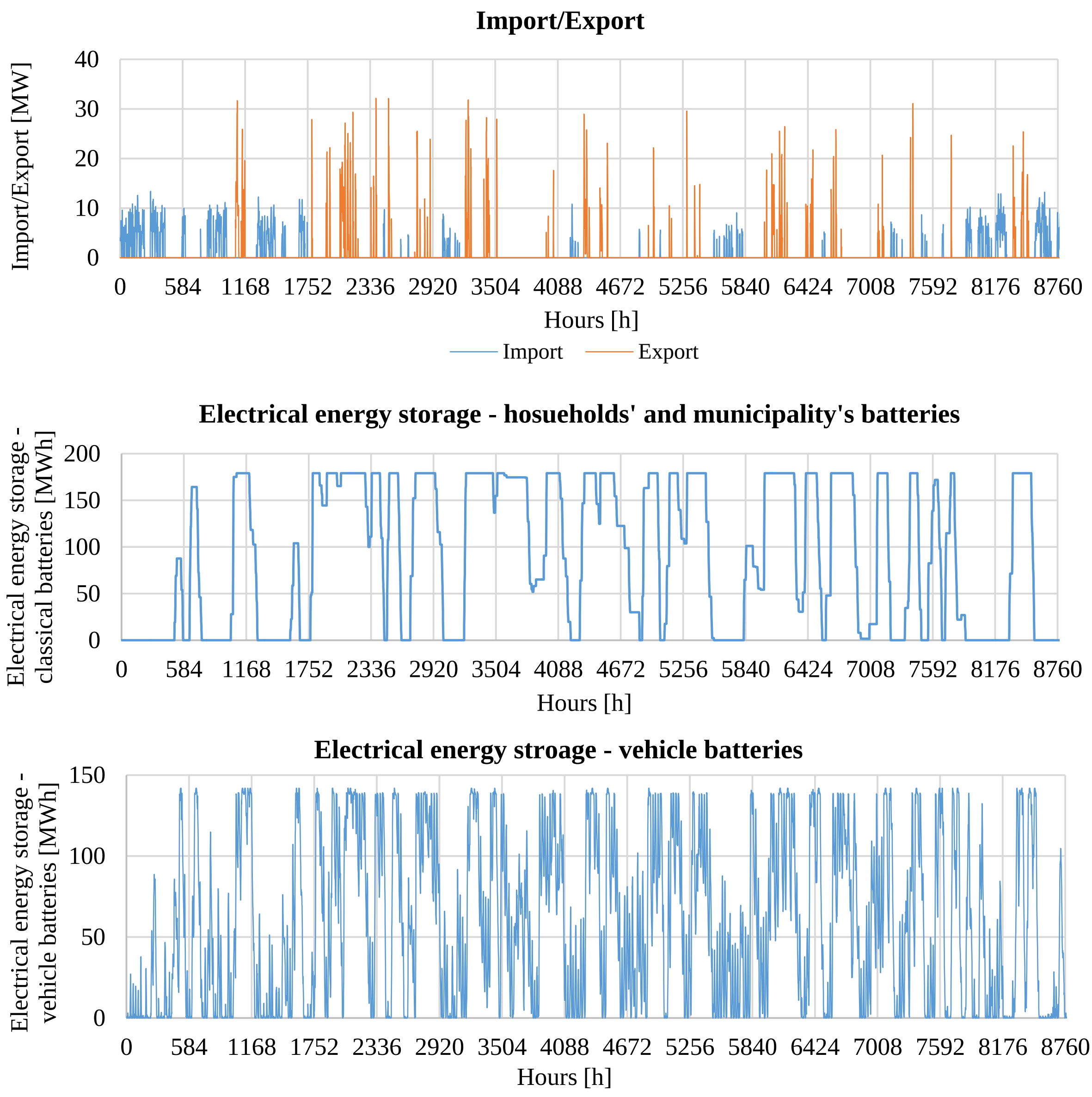

Figure 8 Import/export load and electrical energy storage state of charge – 30 MW of solar and 22 MW of wind

4.4. Energy system evolution

Figure 9 shows evolution of energy system from the 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 unavailability of energy consumption related data. For the purposes of this work, island's SEAP from 2011 was used. This means that the energy consumption and energy system configuration shown in

Figure 9 for the year 2017, doesn't match real historical figures which. For this reason, presented results should be understood as a case study for the proposed method.

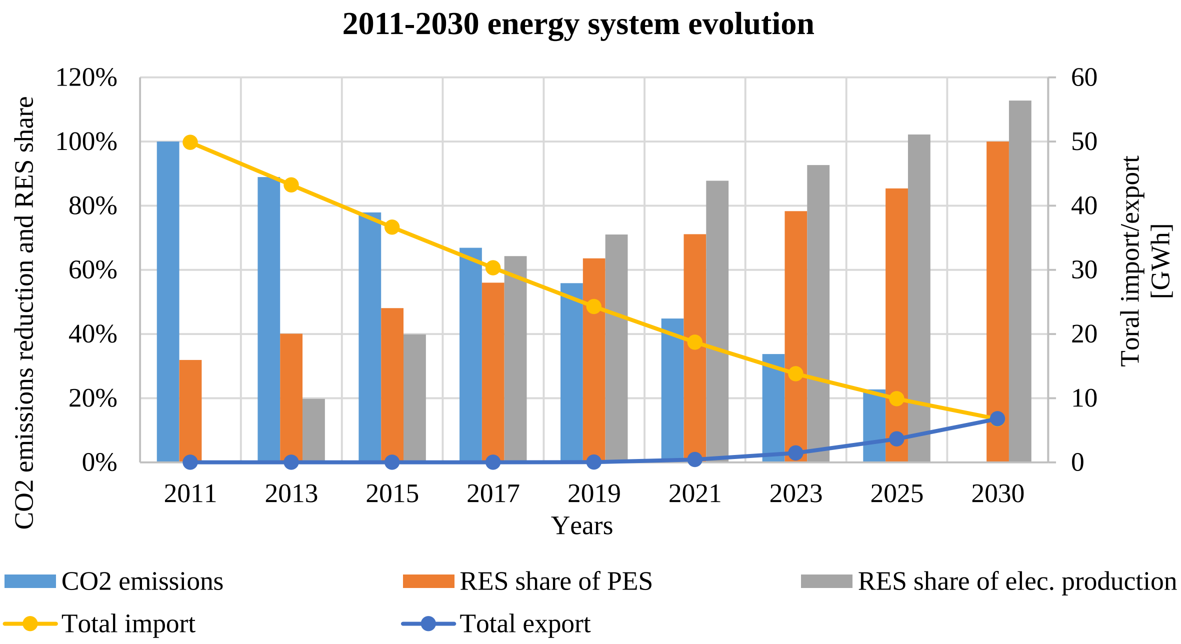

Figure 9 2011-2030 energy system evolution

4.5. Integration of electrical ferry

As described in Chapter Case study, there is great potential of electrifying ferry line Korčula-Pelješac. This chapter shows how the integration of electrical ferry line shifts energy system of the island and its influence on the electricity import and export. Ferry line Korčula-Pelješac is 4 km long and operates every 3 hours all through the 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 [55], proposed ferry has 5 MWh battery and charges only on the island with the 1 MW charger unit. 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 EnergyPLAN tool, where electrical ferries have been modelled as additional capacity to V2G. In order to model hourly distribution, already mentioned ferry time schedule has been used. Electrical ferry has been integrated in the energy system modelled for a final year, 2030, shown in Figure 9.

5. Discussion

Final energy consumption in 2030 has been decreased in every sector, while the biggest energy reduction, equal to 50 GWh, could be noticed in the transport sector, as shown in Table 4. The main reason for this is electrification of personal and public vehicles, i.e. busses on the islands. Energy consumption of the marine transport hasn't been shown, due to the reason that ferries aren't refuelling on the island. Supply capacities have been selected according to the boundary conditions put on the CO_2 neutrality and number of installed stationary and mobile batteries. Electrical energy import and export in the function of installed solar and wind capacities is shown in Figure 1 and Figure 2. According to the input data, wind turbines have higher load factor, equal to 19%, while solar capacities have smaller load factor equal to 14%, i.e. smaller import and higher export could be achieved by using only wind turbines. In order to satisfy condition where import is equal to export, additional plane has been displayed in Figure 3. It shows difference between electricity import and export, i.e. where the surface crosses the x-y plane, import is equal to zero and CO_2 neutrality condition is satisfied. All possible combinations of solar and wind capacities are represented by the red line in Figure 3. In order to acquire the equation which describes this line, constants in Equation 1 had to been calculated. The line which shows all possible combinations of wind and solar capacities could be seen in Figure 4. Lowest possible installed wind capacities is equal to 13 MW, while lowest possible solar capacity is equal to 6 MW. To choose the most suitable supply system configuration, two parameters have been analysed: total investment cost and overall import, i.e. export which are the same. Figure 5 shows relation between installed solar capacity and total cost and energy/import. For every solar capacity shown in Figure 5, wind capacity from Figure 4 should be associated. It could be seen that the cheapest solution could be obtained for 6 MW of installed solar and 40 MW of installed wind. This configuration also have the biggest 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 minimum of cost minimum of import/export couldn't be achieved with the same configuration, these two solutions are chosen for additional analysis of V2G share reduction impact. Figure 6 and Figure 7 show relation between V2G share reduction and electricity import/export for two predefined supply system configurations. It is visible on both figures that for 100% V2G share, total import and total export have the same values. Figure 6 shows V2G share reduction impact for configuration with the lowest total import and export. If V2G share decrease in the final year, total export would increase up to 9.5 GWh, while total import up to 11 GWh. Interestingly, peak import and export load doesn't change as much. Reason for this is that EnergyPLAN only minimizes total import and export load, while peak load isn't taken into account during simulation. As can be seen in Figure 7, which shows similar results for 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 V2G share drops to zero. Also, this configuration also doesn't show big sensitivity of V2G share on import and export peak load. Hourly operation of electrical energy storage and transmission grid load for 30 MW of solar and 22 MW of wind capacity is shown in Figure 8. There is high need for import during winter season due to the excessive use of heat pumps for heating. It could be seen that stationary batteries are depleted and mobile batteries are used for grid balancing. The opposite case is visible during summer period where there is excess of electricity production due to the increased production from solar and wind capacities. Evolution of the energy system which has 100% V2G share, and installed capacity equal to 30 MW of solar and 22 MW of wind is shown in Figure 9. It could be seen that boundary conditions of 100% CO_2 reduction and equalization of import and export are satisfied. It has been showed, once electrical ferry is integrated in the energy system modelled for a final year, 2030, total electrical energy import has been increased to 9.88 GWh, while electrical energy export has been decreased to 4.43 GWh. Electricity import and export peak loads haven't change once the electrical ferry line was integrated.

6. Conclusion

In this paper, an analysis of island system which use 100% intermittent renewable energy sources in combination with 100% share of smart charge vehicles which also include electrical marine transportation has been carried out. This research presents novelty because analysis of the island system with 100% intermittent renewable energy sources hasn't been carried out so far. The tool used for system simulation is EnergyPLAN. Its updated version from November 2017 has possibility of simulating 100% renewable energy systems which utilize only intermittent renewable energy sources in combination with smart charging. Selection of supply capacities hasn't been done by doing scenario analysis but through simple optimization procedure, where two boundary conditions have been defined: supply capacities should include only intermittent renewable energy sources such as solar and wind and total electricity import should be equal to total electricity export. This approach have been tested on the Island of Korčula, located in Korčula. The base year has been chosen as 2011, while final year is 2030. Since there are countless power supply configurations which satisfy given conditions, only two have been chosen. The first one has the lowest total investment: 6 MW of solar and 40 MW of wind. The second one results with lowest total import, i.e. export: 30 MW of solar and 22 MW of wind. For both of them analysis of V2G share reduction has been carried out. In both cases, total electricity import and export has increased with V2G share reduction. This was expected, since other researchers have reported similar results but not with system based on 100% intermittent RES. It is important to notice that import and export peak loads haven't been affected by V2G share reduction. Once electrical ferry line was introduced in the system configuration with 30 MW of solar and 22 MW of wind capacities, electricity export has been reduced, while electricity import has been increased. Reason for this is high share of electrical ferry in energy demand of the transport sector. Electrification of marine transport with smart charge integration could be viable option for larger energy systems where this sector doesn't have such a large share in overall energy consumption.

Acknowledgements

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Annex

Base year consumption input data

In order to calculate energy demand for household sector, additional statistical data is needed. Table 6 shows the statistical data per municipality.

Table 6 Statistical data needed for calculation of energy consumption of household sector

	County				
Input data	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 7 shows additional data needed to calculate the energy consumption of the household sector.

Table 7 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

Data needed to calculate tourism sector final energy consumption on the Island of Korčula is shown in Table 8. Fuel share of Korčula is assumed to be the same as on the Dubrovnik-Neretva County level.

Table 8 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 9 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

Final year scenario input data

In order to calculate the consumption of the average household for energy efficient 2030 scenario, energy renovation measures will have to be defined. It is assumed that 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 [58], total number of households in 2030 is shown in Table 10.

Table 10 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	1,296	1,415	491	2,424	604

Electrical energy demand distribution is acquired by using islands' transformer station. As explained in chapter Method, heating and cooling demand distribution is calculated by using degree-hour analysis.

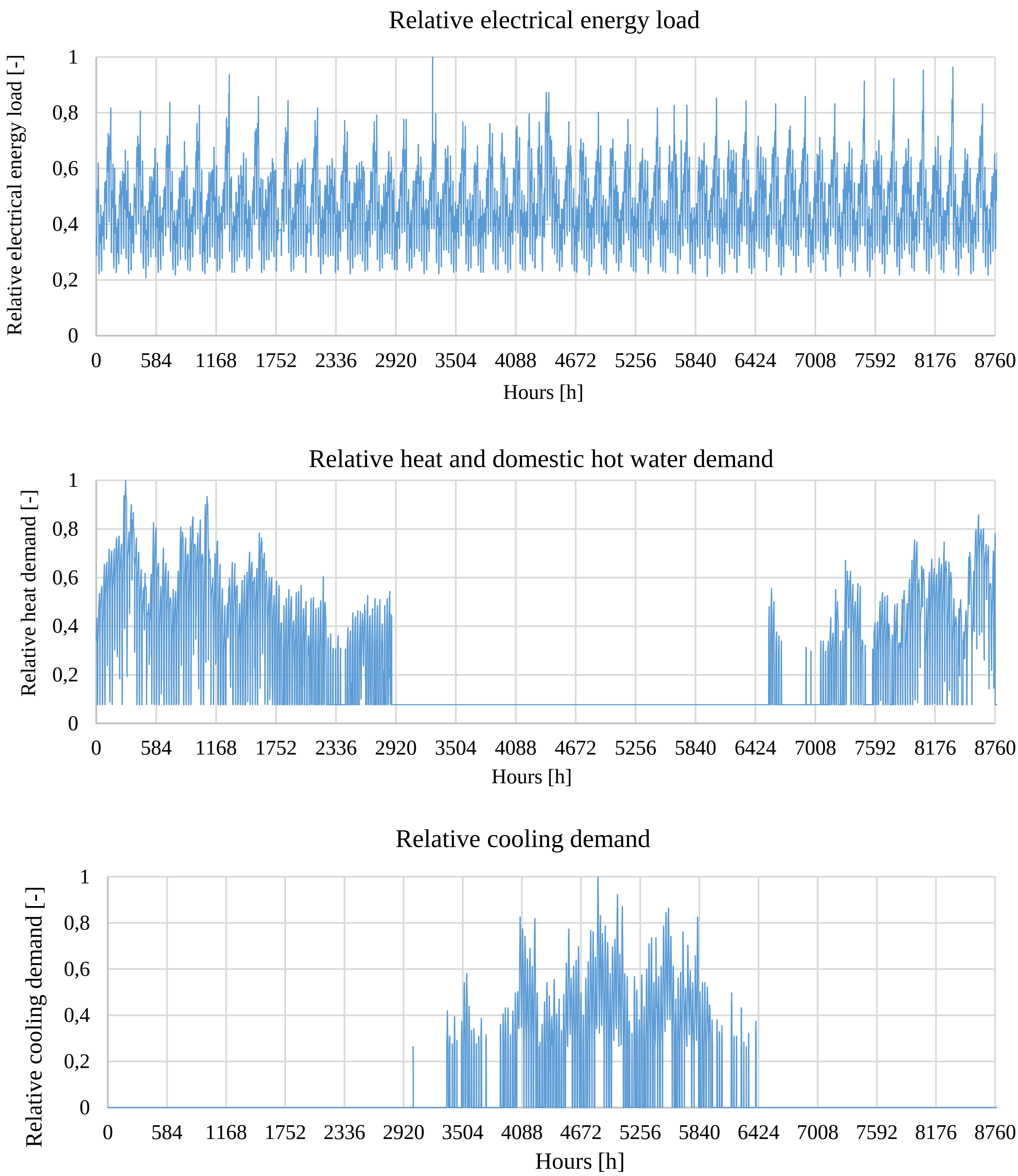


Figure 10 Relative electrical energy, heating and cooling demand

In order to calculate total numbers of overnights in 2030, data from [59] have been extrapolated as shown in Table 11.

Table 11 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

Transport sector input data – 2030 scenario

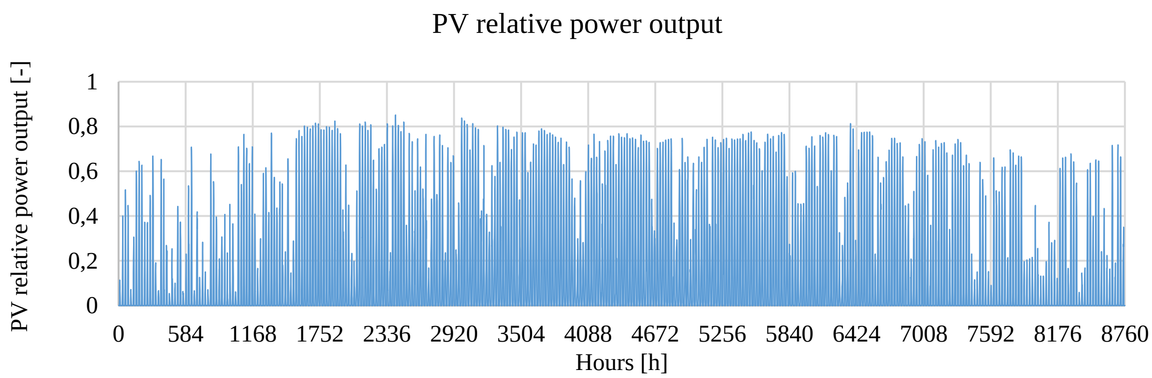
As explained in chapter Method, overall number of vehicles per household will stay the same as in the base year. Final energy consumption for year 2030 is calculated by using overall travelled distance in year 2011 and specific final energy fuel consumption per engine type. Additional assumption is that 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 needed input is shown in Table 12.

Table 12 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 13 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



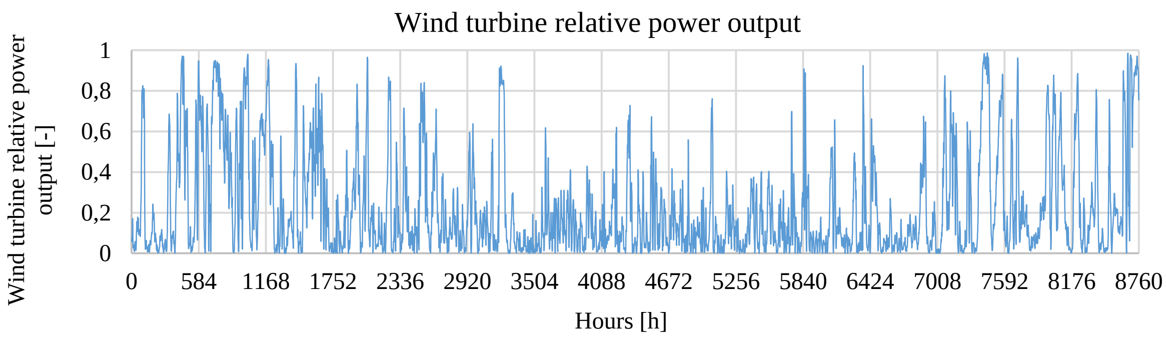


Figure 11 Relative power output of renewable energy sources