The synergy between the photovoltaic power systems and battery-powered electric ferries in the isolated energy system of an island

Lovro Frković[1,*], Boris Ćosić[1,2], Tomislav Pukšec[2], Nikola Vladimir[2]

[1]Center of Technology Transfer LLC, Ivana Lučića 5, 10002 Zagreb, Croatia.
[2]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia.

Abstract

Islands have increased potential to integrate renewable energy sources (RES) into their energy systems and shift towards sustainable decarbonization. The intermittent electricity causes issues such as the mismatch between the energy demand and supply, the grid instability and the electricity price volatility. The integration of the battery-powered electric ferries (BEF) into the isolated energy system (IES) powered with RES can be considered as an economically and environmentally friendly solution for matching the demand with the supply, since all-electric ships can connect to the grid and provide positive or negative balancing power. The carbon dioxide (CO_2) emissions from shipping operations can be reduced to zero by utilizing batteries as a power source. This paper deals with a holistic approach that demonstrates opportunities that implementation of BEF offers in the framework of IES of an island. A method for modelling energy supply for a 100% electric ferry transport is developed to reduce the critical excess electricity production (CEEP) from the photovoltaic (PV) power systems. The energy modelling of the IES was carried out in EnergyPLAN program. The results confirmed that synergy between the PV power systems and BEF can significantly reduce the CEEP, the operating system costs and the emissions of CO_2.

Keywords: Battery-powered electric ferry (BEF), Electrification, Renewable energy sources (RES), Isolated energy system (IES), EnergyPLAN
Word count: 6788

---

[*] Corresponding author.
E-mail address: lovro.frkovic@fsb.hr
Telephone number: +385996855466
Postal address: Center of Technology Transfer LLC, Ivana Lučića 5, 10000 Zagreb, Croatia

Nomenclature

Abbreviations

BEF	Battery-powered electric ferries
CEEP	Critical excess electricity production
CO_2	Carbon dioxide
ECA	Emission control area
EV	Electric vehicle
IES	Isolated energy system
GHG	Greenhouse gas
IMO	International Maritime Organization
PV	Photovoltaic
RES	Renewable energy sources
S2G	Ship-2-Grid
V2G	Vehicle-2-Grid

Variables

BC	Battery capacity (kWh)
BP	Battery price (€/kWh)
EC	Energy consumption (kWh/nm)
IC	Investment costs (€)
l	Length of a round trip (nm)
OC	Operating costs (€)
P	Power (kW)
RT	Number or round trips per day (-)
SD	Number of days per season (-)
SFC	Specific fuel consumption (kg/kWh)
v	Ferry speed (nm/h)

Subscripts

AE	Auxiliary engine
ave	Average
BEF	Battery-powered electric ferry
de	Design
DS	Diesel-powered ferry
FT	Ferry transport
i	Specific ferry route
ME	Main engine
RT	Round trip
RES	Renewable energy sources
tot	total

1. Introduction

The isolated energy system (IES) of an island is faced with number of energy challenges such as lack of fossil fuel electricity generation options, dependence on the mainland's electricity grid and necessity to import fossil fuels [1]. These energy challenges increase the electricity price, consumption of fossil fuel in the transport sector and concentration of carbon dioxide (CO_2) in the atmosphere [2]. Generally, most islands could cover their energy consumption and become energy self-sufficient by deriving energy from renewable energy sources (RES). The Clean Energy for EU islands initiative [3] promotes the model of energy self-sufficient islands, the reduction of fossil fuel imports and the integration of RES. The Smart Island Initiative [4] framed the energy transition of islands and demonstrated that islands should be considered as living labs that can offer new solutions for sectors such as energy and transport to mitigate impacts of global warming and climate change on their ecosystems [5]. The sustainable development pathways of the IES requires a holistic approach that exploits synergies between different energy sectors [6]. The special focus should be set on the power sector and the transport sector. According to the Article 3 of the Renewable Energy Directive (RED II) directive [7], Member States of the European Union (EU) shall collectively ensure that the share of energy from renewable energy sources in the Union's gross final consumption of energy in 2030 is at least 32%. The directive includes obligations on fuel suppliers to supply at least 14% of the energy consumed in road and rail transport by 2030 as renewable energy [8].

The maritime transport is not a subject to an obligation. However, this mode of transport should also opt in to contribute to the 14% target. Article 1 of the proposal for a FuelEU Maritime [9] lays down rules aiming to reduce the greenhouse gas (GHG) emissions on-board ships arriving at, within or departing from ports under the jurisdiction of a Member State to promote the development and consistent use of renewable energy. These requirements put pressure on the Member States to integrate higher share of intermittent RES such as solar and wind into their power sectors [10], as well as alternative powering options into their transport sectors to achieve sustainable decarbonization of the IES [11].

1.1. The IES of an island powered with 100% RES

The integration of RES is recognized as a solution that creates energy savings both on the demand and supply side, improves the energy efficiency and reduces the consumption of fossil fuel in the power sector [12]. Study by Hoang et al. [13] highlighted that integration of RES into energy systems can decrease carbon footprint and emissions of other toxic pollutants with minimal impacts on the environment. The study concluded that energy systems powered with RES should be able to optimize, coordinate and control the interconversion and distribution of multiple energy sectors to overcome challenges and improve energy efficiency. Mahmood et al. [14] reviewed the optimization strategies for integrating RES and highlighted the following challenges: location selection, sizing of the renewable-based energy system, uncertainty in matching the energy supply with demand, power outage and diversity in renewable technologies.

The electricity production from RES depends on changeable weather conditions [15]. The intermittency of the weather conditions can cause a mismatch between the electricity supply and demand [16]. Therefore, the integration of additional storage capacities into the IES is required to match the electricity generation from RES with the demand and advance stability of the power grid. The study by Gomes et al. [17] demonstrated the integration of RES and battery storages in the specific region of Azores and concluded that a combination of RES generation power systems and energy storages can decrease power capacities of the dispatchable power systems based on fossil fuel. Ajanovic et al. [18] analysed the implementation of different energy storages into energy systems and concluded that decentralized battery storages connected to Photovoltaic (PV) power systems are not the most economically viable option since the number of full-load hours is relatively low. The integration of battery storages increases the electricity price and costs of the overall IES and sets up limitations on the maximum share of RES in the energy mix.

The study by Bertheuau [19] concluded that energy systems with 100% RES are characterized by increased share of the excess electricity production that needs to be minimized to further reduce energy system costs. The study conducted by Wang et al. [20] investigated decarbonized electricity systems and highlighted that implementation of energy storages for storing the Critical Excess Electricity Production (CEEP) is not the most economical approach. Therefore, the holistic approach that facilitates synergies between different energy sectors is required to demonstrate environmentally and economically viable energy transition of islands. Mimica et al. [21] used the Smart Islands method to define energy planning scenarios on islands and showed that available flexibility of the system can be increased by coupling different energy sectors. Study by Alves et al. [22] demonstrated that interconnection between the power systems of the Azorean islands can increase share of RES in their IES, and eventually eliminate the consumption of fossil fuel.

Dominković et. al. [23] investigated the future of transport in energy systems and indicated electrification of the transport sector as the most important solution for sustainable energy transition. Yuan et al. [24] investigated the electrification of the transport sector along with the energy transition and concluded that integration of Electric Vehicles (EV) and RES can reduce CO_2 emissions and create energy savings. The study presented in [25] explored connections between the transport sector and RES and showed that smart charging strategies open the possibility to utilize EV capacities as battery storage systems. The study by Shi et al. [26] investigated integration of RES and EV into energy system and proposed a strategy that facilitates Vehicle-2-Grid (V2G) technology for improving the security and economy of the microgrid systems. Fachrizal et al. [15] reviewed the state-of-the-art smart charging strategies and proposed solutions that can increase PV utilization, decrease peak loads and reduce the electricity prices. Hrnčić et al. [27] achieved a 100% renewable energy system by facilitating the synergy between the power sector and the transport sector and demonstrated how the percentage of CEEP correlates with different levels of the installed PV power plants and shares of V2G connections.

1.2. The implementation of BEF into the IES of an island

The short-sea shipping refers to maritime transport of goods, cars and passengers over relatively short distances. In 2018, the total weight of goods transported to or from the main ports in the European Union Member States (EU-27) by this mode of shipping was around 1.8 billion tonnes and accounted for 59% of total EU-27 maritime goods transport [28]. This mode of transport is generally enabled with conventional ships powered with diesel engines that consume significant amounts of fossil fuel and consequently cause air pollution, global warming and climate change [29]. In 2018, maritime transport emitted around 1,056 million tonnes of CO_2 and was responsible for almost 3% of global greenhouse gas (GHG) emissions [30]. Shipping has a prominently negative effects on human health [31], since it is responsible for approximately 15% of the global nitrogen oxides (NO_x) and 13% of the global sulphur oxide (SO_x) emissions [32]. The International Maritime Organization (IMO) established Emission Control Areas (ECAs) to progressively reduce air pollution that originates from conventional ships with diesel engines. In 2020, the IMO limited the mass percent of sulphur in the fuel oil used on ships that are operating inside of the ECAs to 0.10% [33].

The restrictions that regulate pollution from ships are increasing the pressure at the EU level to replace conventional diesel-powered systems with alternative powering options [34]. The study by Bach et al. [35] compared the battery-powered and hydrogen-powered systems for Norwegian costal maritime transport and concluded that batteries are not only more mature technology, but also have increased potential to advance in the future. The study by Fan et al. [36] indicated that 100% electric ship with a battery as a power source has decreased CO_2 emissions and lower costs compared to the hybrid-powered and the conventional diesel-powered ship systems. Perčić et al. [37] conducted Life-Cycle Cost Assessment (LCCA) of the diesel-powered system, the battery-powered system and the battery-powered system with PV cells on board. The results highlighted the battery-powered system as the most environmentally friendly and economically viable powering system for the Croatian short-sea shipping sector. The study by Wang et al. [38] also confirmed, with a certain set of assumptions, that a battery-powered ship is both the most ecological and economical option. Zubi et al. [39] investigated state-of-the-art Lithium-ion (Li-ion) batteries and indicated that batteries have global potential for achieving the energy sustainability and carbon footprint reduction in the transport sector. Perčić et al. [40] performed Life-Cycle Assessment (LCA) and LCCA of different battery powering options for short-sea shipping and highlighted electrification by a Li-ion battery as the most appropriate one in terms of environmental and economic performance.

The European Maritime Safety Agency (EMSA) reported that battery power is convenient for ferry electrification since these ships operate on a relatively short and scheduled voyages with sufficient time for battery charging [41]. Pfeifer et al. [42] presented a method for modeling electricity supply for zero-emission ferry voyages and indicated that electric ferries have the lowest operation costs when compared to hydrogen or diesel ferries. The study by Gomes et al. [43] demonstrated that accumulated battery capacity of the 100% electric fleet can store surplus of electricity produced by PV power systems during the day and return it to the grid to shave peak loads. The battery-powered electric ferries (BEF) can be perceived as mobile battery storage capacities that can connect to the grid and store energy during excess of electricity production or supply energy during shortage of electricity production. Therefore, the implementation of the BEF should be considered as a sustainable solution for achieving the decarbonization of the ferry transport and improving the stability of the electricity grid.

1.3. Research gap and contribution of the paper

After a comprehensive literature review, it is evident that the replacement of diesel-powered systems with battery-powered ones can create environmental and economic benefits for the maritime transport sector. The implementation of battery-powered systems is a trending topic in road transport, but research on their implementation in short-sea shipping is underrepresented. This paper investigates the implementation of BEF into the IES powered with 100% RES to demonstrate environmental and economic benefits for both the short-sea shipping and the power sector. Based on the literature review, the following research gaps have been identified:

- The electrification of the short-sea shipping is desirable, but there is no clear insight into the viability of this process considering its impacts on isolated power grids,
- The integration of a higher share of RES into the IES is beneficial, but there are still no unified solutions for matching sustainable energy supply and demand for randomly selected IES powered with 100% RES,
- References dealing with the short-sea shipping electrification regularly underestimate the problem of intermittent energy supply, and to the best of authors' knowledge, there is no reference simultaneously considering integration of large energy consumers like all-electric ships into the IES of islands, particularly if they include different shares of RES.
- There is a need for an accurate model to determine the environmental and economic impact of the implementation of BEF into the IES powered with 100% RES,
- Even though the Croatian short-sea shipping sector has increased potential for being 100% electric, there are no relevant studies examining appropriate implementation strategies to reduce its environmental impact in a cost-effective way.

This paper aims to tackle mentioned research gaps, by considering transition to 100% electric ferry transport powered with CEEP from RES installed in the IES of an island. The goal is to create economically and environmentally sustainable solution, which can be applied to different IES. The original contribution of this paper includes:

- A model for demonstrating the synergy between the IES powered with 100% RES and the 100% electric ferry transport powered with batteries,
- An insight into the viability of reducing the environmental impact of both sectors through the implementation of BEF and integration of RES,

- An alternative IES of an island that considers transition to renewable-based power sector and electrification of the corresponding ferry voyages in Croatia.

The study deals with the specific IES of an island powered with a high share of PV power systems and considers electrification of the corresponding ferry voyages through implementation of BEF and Ship-2-Grid (S2G) charging strategies to reduce the CEEP, transmission line congestions and energy losses. The charging cycles of BEF need to be investigated to match the planned electricity production with the ferry transport demand. The results showed that installed capacities of the PV power systems could generate enough electricity to cover the demand of the island and the demand of the 100% electric ferry transport. The study brings scientific contribution to the cleaner short-sea shipping by implementing BEF into the island grid, which is shown to be beneficial both from the economic and environmental point of view. Each island and corresponding shipping routes should be considered as a unique system. The methodology is applicable more generally if a set of input data relevant for some other island is known. The modelling was conducted for the specific case study of the Island of Cres, located in Croatia.

2. Method

The EnergyPLAN program is a simulation tool that demonstrates the operation of a specific IES to supply the range of energy demands [44]. The program was used to investigate impacts of implementing BEF into the IES powered with PV power systems. The method is developed to evaluate the IES in hourly steps for one year, and it should be separated into several development stages to define energy consumption of the reference year, calculate energy consumption for the projected year and optimize the electricity supply and demand capacities for the projected year scenarios with a given set of boundaries. The model aims to match the electricity generation from PV power systems with the demand of the IES through implementation of BEF, which can be considered as additional demand or battery storage capacities. To evaluate the nexus between S2G strategy and PV power systems, the model requires hour by hour data for the entire year to determine when BEF can be connected to the grid and provide feedback or storage of electricity. Many studies are focused on calculating maritime transport electricity demand, and different methods were considered [45], [46]. For the purpose of this study, the IES analyses the power sector and the ferry transport sector. The method is schematically presented in Figure 1.

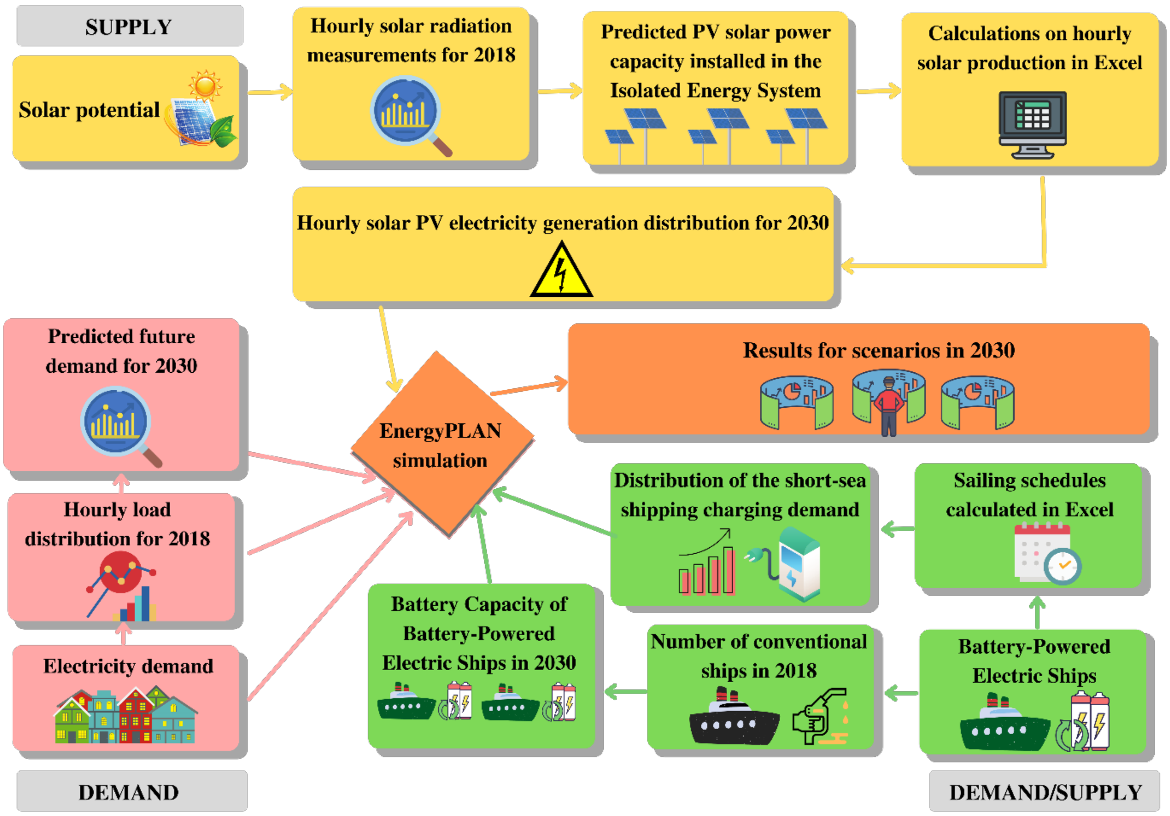

Figure 1. Methodology flow chart

The presented method requires the calculation of the ferry transport demand. According to the ferry operating schedules and voyage durations, the average ferry operative speed v_{ave} (nm/h) differs from the ferry design speed v_{de} (nm/h), and can be calculated by using Eq. (1):

$$v_{ave} = \frac{l}{t}, \tag{1}$$

where l (nm) is the length of the voyage and t (h) is duration of the voyage. The average main engine power, $P_{ME,ave}$ (kW) [36] can be calculated according to Eq. (2):

$$P_{ME,ave} = (P_{ME} \cdot 0.8\,) \cdot \left(\frac{v_{ave}}{v_{de}}\right)^3, \tag{2}$$

where P_{ME} (kW) is the main engine power. The average load of the additional auxiliary engines, $P_{AE,ave}$ (kW) is assumed to be 60%. The average ship power, P_{ave} (kW) can be calculated by summing up the $P_{ME,ave}$ and the $P_{AE,ave}$. The energy consumption of a ferry, EC_i (kWh/nm) [40] can be calculated as in Eq. (3):

$$EC_i = \frac{P_{ave,i}}{v_{ave,i}}. \tag{3}$$

The annual distance travelled by a particular ferry, $l_{annual,i}$ (nm) can be calculated by multiplying the length of the round trip, $l_{RT,i}$ (nm), the daily number of round trips in a particular operating season, $RT_{i,j}$ and the annual number of operating days in a particular season, $SD_{i,j}$ according to Eq. (4):

$$l_{annual,i} = \sum l_{RT,i} \cdot (RT_{i,j} \cdot SD_{i,j}), \tag{4}$$

The subscription i represents a ferry that operates on a particular route, while subscription j represents the operating season with specific shipping schedules defined by shipping companies that ensure maritime transport, i.e. low-season, pre-season or high-season.

The total annual energy consumption of the ferry transport, $EC_{FT,tot}$ (kWh) can be calculated according to Eq. (5):

$$EC_{FT,tot} = \sum n_i \cdot EC_i \cdot l_{annual,i}, \tag{5}$$

where n_i refers to the number of specific ferries that are operating on the ferry route.

The ferry transport is assumed to be 100% electric by 2030. Therefore, the conventional ferries need to be replaced with the BEF. The battery capacity of the BEF is an important data for calculating the 100% electric ferry transport demand and it is calculated for each route separately. The required battery capacity, $BC_{BEF,i}$ (kWh) is calculated according to Eq. (6):

$$BC_{BEF,i} = 1.5 \cdot EC_i \cdot l_{RT,i}, \tag{6}$$

where $l_{RT,i}$ (nm) refers to the length of a round trip and EC_i (kWh/nm) denotes the energy consumption of a ferry. The subscription i represents a ferry operating on a particular route.

The S2G model utilizes electricity connection between the BEF and the shore infrastructure to charge the 100% electric fleet during periods of surplus electricity production or to discharge it during periods of peak loads. The CEEP is the surplus of electricity produced from RES that cannot be exported to the mainland. The capacity values of the energy transmission lines were not set, so the excess of electricity produced throughout the whole year is observed as critical. The S2G model is based on the ferry route departure schedules and periods of the day when BEF are at the port and connected to the power grid. The smart charge model within the EnergyPLAN program includes S2G in the production system and allows that S2G ferries are recharged at the time of available CEEP and available battery storage capacity [30].The inputs for defining BEF with S2G in the EnergyPLAN are presented in Table 1.

Table 1. The inputs for the S2G model

D_{S2G}	The ferry transport demand of S2G ferries in GWh/year (defined as electricity demand from the grid).
δ_{S2G}	The distribution of the ferry transport demand in 8784 hourly values. These values are relative and range from 0 to 1.
$C_{Charger}$	The capacity of the grid connection in MW.
$\mathrm{S2G}_{\mathrm{MaxShare}}$	The maximum share of S2G ferries which are driving during peak demand hour.
$\mu_{Charger}$	The efficiency of the grid to battery connection (charger).
$\mu_{Inverter}$	The efficiency of the battery to grid connection (inverter).
$\mathrm{S}_{\mathrm{S2G\text{-}Battery}}$	The capacity of the battery storage in MWh.
$\mathrm{S2G}_{\mathrm{Connection\text{-}Share}}$	The share of S2G ferries at berth and connected to the grid.

The distribution of the ferry transport demand, δ_{S2G} was modelled in 8784 hourly values for the year 2018 on the basis of the acquired ferry departure schedules, voyage lengths and durations, and the daily number of round trips during low-season, pre-season, and high-season. The δ_{S2G} represents S2G ferries that are in operation and not available to connect to the grid at the specific hour. The distribution can be used to determine the battery discharging profiles caused by ferry route operations. The fraction of the S2G fleet available to the power system at any given hour is determined by the maximum share of S2G ferries that are in operation during peak hour, $\mathrm{S2G}_{\mathrm{Max\text{-}Share}}$ and the share of S2G ferries that are connected to the grid, $\mathrm{S2G}_{\mathrm{Connection\text{-}Share}}$. The maximum system capacity, $\mathrm{C}_{\mathrm{Charger}}$, is calculated based on the maximum power of a single ferry multiplied by the maximum number of ferries plugged in at any given time. For the purposes of this study, it is assumed that a ferry will connect to the grid and fully charge after each round trip. Therefore, one additional ferry is added on each route to ensure sufficient time for charging, so when one ferry is connected to the grid and charging, the other one is operating. The number of charging cycles per day (Ch_{i}) is defined by the daily number of round trips in a particular operating season, so it varies depending on the specific shipping schedules predefined by shipping companies. The batteries of the S2G ferries are grouped and considered as one battery with accumulated capacity.

The production (e_{Total}) represents the sum of all the renewable electricity production in the IES and can be calculated by using Eq. (7):

$$e_{Total} = e_{Res} = \sum_{i=1}^{n} e_{RES,i} \tag{7}$$

The total demand of the IES (d_{Total}) is the sum of the electricity demand (d_E) and the ferry transport demand which includes the flexible ferry transport demand (d_{FX}), the smart charge demand (d_{smart_charge}) and the S2G demand (d_{S2G}), and can be calculated as in Eq. (8):

$$d_{Total} = d_E + d_{FX} + d_{Smart\ Charge} + d_{S2G} \tag{8}$$

The difference between the demand and the production represents an excess or a deficit in the electricity production, depending on whether less or more energy is produced in a particular period than it is needed, and it is calculated by using Eq. (9):

$$e_{CEEP} = d_{Total} - e_{Total} \tag{9}$$

3. Case study

The case study demonstrates the IES of the Island of Cres located in Croatia. The island is connected to the electricity grid of the Island of Krk with a 35 kV subsea transmission power cable. The electricity is transformed from high to medium voltage through a substation 35/10 (20) kV Cres. The input data for the EnergyPLAN program such as the demand of the considered energy sectors and the capacities of the planned RES power systems were acquired from the Development strategy of the island of Cres for the period from 2015 to 2020 [47] and from the Sustainable Energy Action Plan (SEAP) of the city of Cres until 2020 [48]. Additional input data for the EnergyPLAN was collected for the year 2018 from the Energy transition plan of the Cres-Lošinj archipelago [49], and it was calculated in the Excel program for the year 2030 based on the acquired rates of change for different inputs [50].

3.1. Solar potential

The Island of Cres has around 2300 sun hours per year, and with more than 1450 kWh/m^2 of annual global horizontal irradiation it is one of the most insulated islands in Croatia. The average annual temperature is 14.5 °C. The coldest month is February with the lowest average temperature of 6 °C, while the warmest month is July with the highest average temperature of 24.3 °C. The supply of the IES was modelled according to the capacities of the PV power systems that are planned to be installed on the island by the year 2030 (Table 2). The hourly distribution curve of the PV power systems production was developed based on the solar irradiation measurement data obtained from the Photovoltaic Geographical Information System (PVGIS) for the year 2016 [51].

Table 2. The capacity of the PV power systems installed on the Island of Cres [49]

Name of the PV power system	Capacity [MW]
Orlec-Trinket - East	6.5
Orlec-Trinket - West	4.5
Ustrine	10
Total	21

3.2. Electricity demand of the IES

The hourly electricity demand distribution curve for the Island of Cres was obtained from the measurements of the substation 35/10 (20) kV Cres. The measurements were provided in hourly values for the year 2018 by the Croatian national electricity company HEP Group (HEP d.d. – Hrvatska elektroprivreda d.d.) [52]. Hourly distribution curve of the electricity demand was developed in Excel for the year 2018 in accordance with the obtained data. The total demand of the IES in 2018 was 17.01 GWh/year and the maximum power demand reached 5 MW during summer period, as shown in Figure 2.

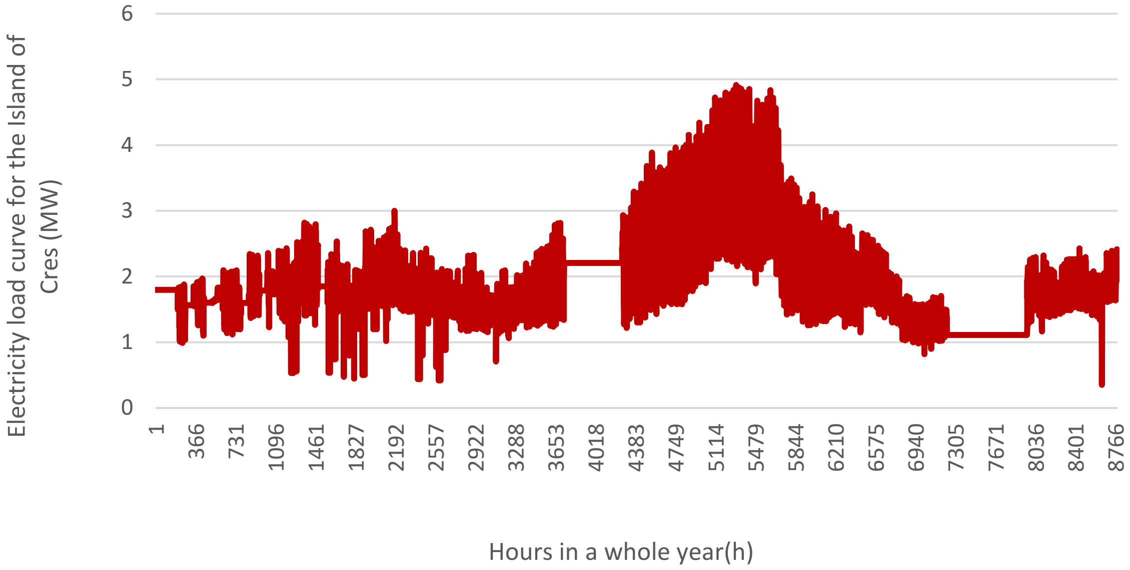

Figure 2. The electricity demand of the Island of Cres for the year 2018

The min-max normalization is performed to demonstrate the relationship between the following attributes: electricity demand and solar irradiation. The comparison of the min-max normalization of the electricity demand and solar irradiation for the year 2018 is shown in Figure 3. The min-max normalization demonstrates convenient correlation between the electricity demand of the island and solar irradiation during summer period, since both the load and the solar irradiation are high. The correlation between the electricity demand and solar irradiation values is inconvenient in April, May, and June, since the electricity demand curve is lower than solar irradiation curve (the CEEP from PV power systems is expected to occur).

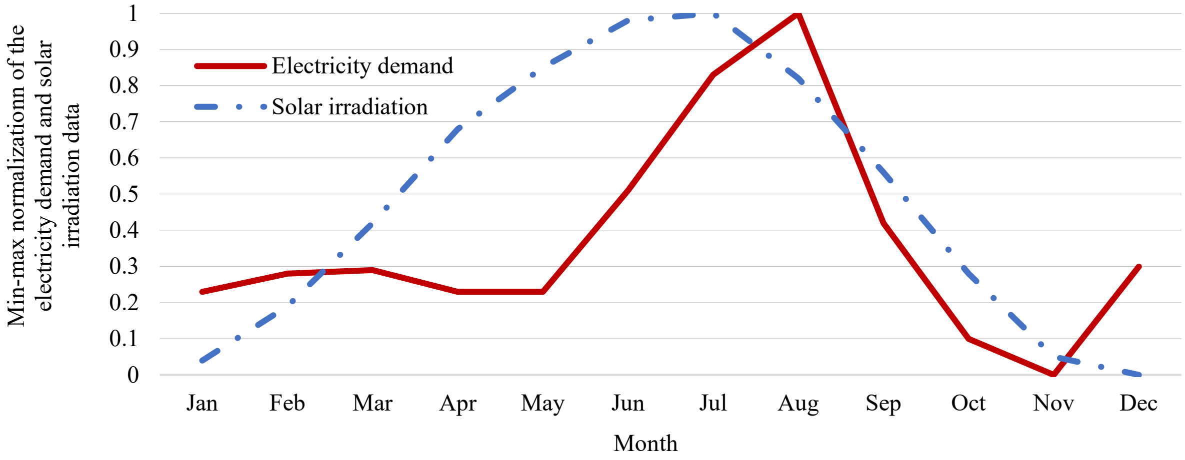

Figure 3. Min-max normalization of the electricity demand and solar irradiation data

3.3. The ferry transport demand

The characteristics of the selected ferry routes and the list of ferries that operate on these routes are obtained from the Croatian shipping company Jadrolinija [53]. Technical specifications of the conventional ferries are acquired from the Croatian register of shipping [54]. According to the analysed data, the connectivity of the island is ensured by two ferries that operate on two different routes, as shown in Table 3.

Table 3. Characteristics of the analysed ferry routes [53] and conventional ferries [54]

Route type		Ferry line	Ferry line
Route identification number		332	334
Depart location		Valbiska (Island of Krk)	Brestova (Istrian peninsula)
Arrive Location		Merag (Cres)	Porozina (Island of Cres)
Number of round trips	**Low-season**	10 [55]	8 [56]
	Pre-season	12 [55]	11 [56]
	High-season	17 [55]	13 [56]
Number of passengers transported		1,178,572.00	602,591.00
Number of vehicles transported		468,070.00	234,561.00
Route distance [nm]		3,63	2,7
Ferry no.		Ferry 1	Ferry 2
Ferry name		KRK	BOL
Ferry type		Ro-Ro/Passenger Ship	Ro-Ro/Passenger Ship
Length between perpendiculars, *Lpp* [m]		89.1	72.89
Breadth, *B* [m]		17.5	20
Draught, *T* [m]		2.4	3.6

Main engine power, P_{ME} [kW]	1764	1412
Auxiliary engine power, P_{AE} [kW]	1080	400
Design speed, v_{de} [kn]	12.3	12
Trip duration, *t* [min]	25	20
Route length, *l* [nm]	3.63	2.7
Annual number of return trips, *Na*	4758	3904
Lifetime, *LT* [years]	20	20
Ship capacity	616 passengers, 145 vehicles	600 passengers, 176 vehicles

Following their battery size, the ferries were grouped per route on which they operate as shown in Table 4. The average daily trip of ferries on line 332 is calculated to be 94.38 nm, while the average daily trip of ferries on line 334 is calculated to be 57.60 nm.

Table 4. The battery characteristics of the BEF

Route identification number	332	334
Battery type	Lithium-ion (Li-ion)	Lithium-ion (Li-ion)
Number of battery cycles in a lifetime	9,000 [57]	9,000 [57]
Specific energy [Wh/kg]	250 [58]	250 [58]
Battery cost, [€/kWh]	200 [57]	200 [57]
Battery Capacity, [kWh]	1706.81	667.40
Required range, [nm]	7.26	5.40
Energy consumption per round trip, [kWh/nm]	1137.87	444.94
Number of ferries operating on the route	2	2

3.4. Investment and fixed operating costs

The investment and fixed operating costs are calculated for the diesel-powered ferries that operate on the selected ferry routes. The results are inserted into the EnergyPLAN program. The investment cost, IC_{DF} (€) of a diesel-powered ferry includes purchase of a diesel engine and it is a result of multiplying the assumed conversion factor of 250 €/kW with the calculated average ferry power. The operating costs, OC_{DF} (€) of a diesel-powered ferry are consisted of the maintenance cost and fuel consumption costs. The study by Iannaccone et al. [59] indicated that annual maintenance cost can be calculated by multiplying the ferry's annual energy consumption with a specific maintenance cost of 0.014 €/kWh. A diesel-powered ferry's annual fuel consumption costs are calculated by multiplying the annual ferry' energy consumption, the assumed specific fuel consumption for diesel engines 0.27 kg/kWh [58] and the estimation of diesel price of 32 €/GJ for 2030 [59]. The average price of diesel fuel in Croatia reached 1.77 €/l in 2022 [58].

The calculation of the investment and fixed operating costs for BEF is based on the battery characteristics shown in Table 4. Approximately 45% of the investment costs of a BEF refer to the costs of the battery storage [62]. Therefore, the total investment costs of a BEF, IC_{BEF} (€) can be calculated by using the Eq. (10):

$$IC_{BEF} = \frac{BP}{0.45}, \tag{10}$$

where BP (€/kWh) is a battery price, which is calculated by multiplying the BC (kWh) with the battery cost. The maintenance costs of the battery-powered system refer to the battery replacement costs during ferry's lifespan. The annual electricity cost is calculated by multiplying the annual energy consumption with the Croatian electricity price of 0.078 €/kWh [59]. Additional input data for the EnergyPLAN program cost analysis is the assumed price of CO_2 emissions of 180 €/t for the year 2030 [63].

4. Results and discussion

The results presented in this section were developed to demonstrate reduction of the CEEP by facilitating the synergy between the IES powered with 100% RES and the 100% electric ferry transport powered with batteries. The scenarios were developed for one specific year to present the impacts of implementing BEF and PV power systems into the IES of an island. The annual demand capacities are shown in Table 5.

Table 5. Electricity and ferry transport demand for defined scenarios

Scenario no.	**Ref**	**1**	**2**	**3**
Year	2018	2030	2030	2030
Electricity demand [GWh/year]	18.55	18.04	18.04	18.04
Diesel-powered ferry transport demand [GWh/year]	6.55	6.55	6.55	0
Battery-Powered Electric Ferry demand [GWh/year]	0	0	0	7.28
Total Electricity demand of the IES [GWh/year]	18.55	18.04	18.04	25.33

4.1. Scenario 1: The business as usual 2030

The business as usual 2030 scenario demonstrates the IES of the Island of Cres for the year 2030. The local RES power system capacities were not installed on the island in this scenario. The electricity demand of 18.04 GWh/year was imported to the IES from the mainland. The total energy consumption of the diesel fuel required for the ferry transport was 6.55 GWh. The average monthly values of the electricity demand and the electricity import were obtained from the EnergyPLAN simulation (Figure 4).

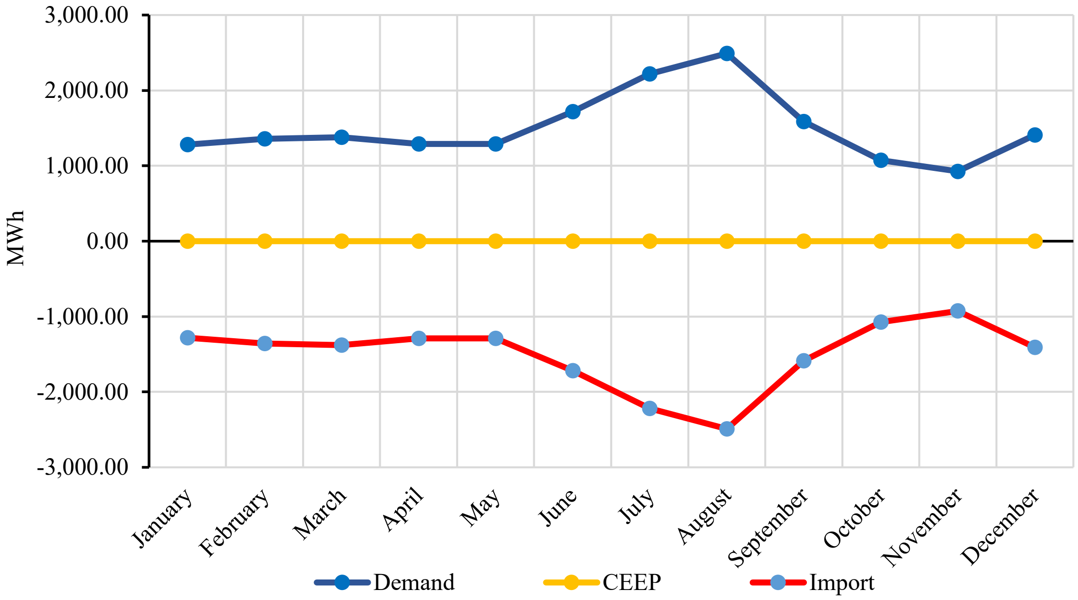

Figure 4. The average monthly values of the electricity demand and import for the scenario 1: The business as usual 2030

The electricity demand is presented with the blue curve, while the import of the electricity is presented with the red curve. The only difference between these average monthly values is that the import of electricity is presented with negative monthly values, since the electricity production facilities are not installed on the island and the electricity needs to be imported from the mainland. The peak demand occurs between August and September, which was expected because of the increased number of tourists on the island during summer months. The annual values for the business as usual 2030 scenario are presented in Table 6.

Table 6. The annual values of the scenario 1: The business as usual 2030

Scenario no.	1
Scenario name	The business as usual 2030
Year	2030
Electricity demand [GWh/year]	18.04
Annual electricity production [GWh/year]	0
Import of electricity [GWh/year]	-18.04
Export of electricity [GW/year]	0
Diesel-powered ferry transport demand [GWh/year]	6.55
Battery-Powered Electric Ferry demand [GWh/year]	0

The business as usual 2030 scenario required annual investment costs of € 3,414,000.00. The annual costs consist of the electricity import costs, diesel consumption costs and CO_2 emission costs and their values are shown in Table 7.

Table 7. The annual costs of the IES for the scenario 1: The business as usual 2030

Scenario no.	1
Scenario name	The business as usual 2030
Cost type	Annual value
Electricity import costs	2,345,000.00€
Diesel-powered ferry transport fuel costs	755,000.00 €
CO_2 emission costs	314,000.00 €
Total	3,414,000.00 €

From the costs analysis it can be obtained that 69% of the annual costs refer to the electricity import costs, 22% refers to the diesel costs required for conventional ferry operations and 9% refers to the CO_2 emission costs. The shares of individual annual costs for business as usual 2030 scenario are shown in Figure 5.

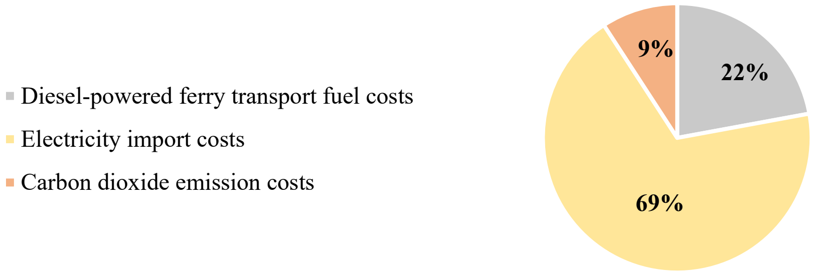

Figure 5. Shares of the individual annual costs of the IES for the scenario 1: The business as usual 2030

4.2. Scenario 2: The PV power systems 2030

The PV power systems 2030 scenario demonstrated integration of the PV power systems with the total capacity of 21 MW into the IES of the Island of Cres. The electricity production from the total installed capacities was calculated to be 30.67 GWh/year. The total energy consumption of the diesel-powered ferry transport is not affected by the integration of PV power systems and it remained 6.55 GWh/year, as in the business as usual 2030 scenario. These PV power systems are intended to supply the electricity demand of the island. It is assumed that surplus of electricity production cannot be exported to the mainland. Therefore, the excess of electricity production is considered as CEEP. The average monthly values of the electricity demand, import, export and CEEP for scenario 2 were obtained from the EnergyPLAN simulation (Figure 6).

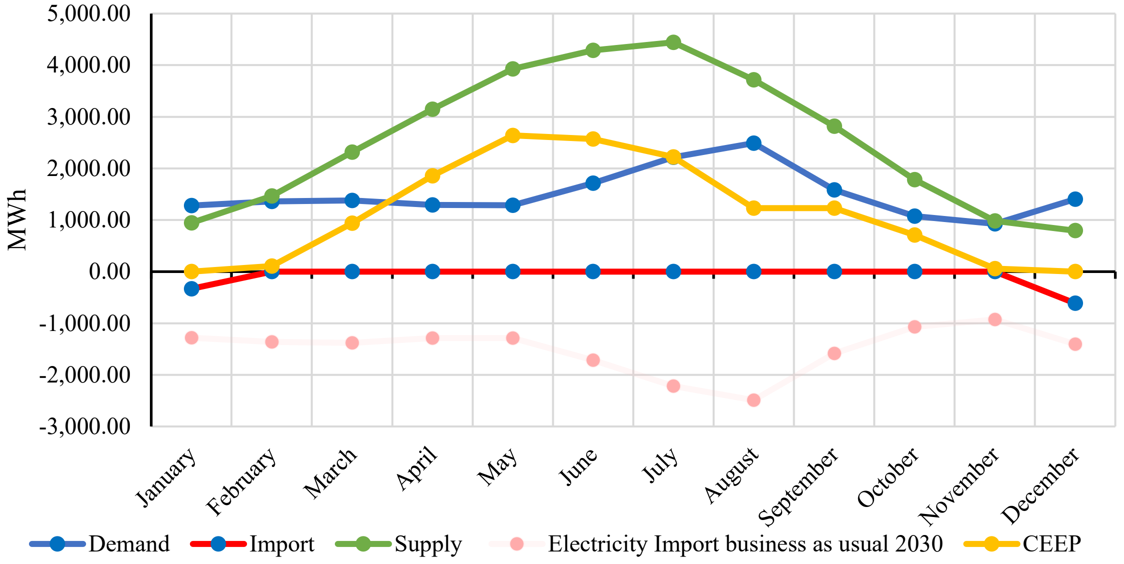

Figure 6. The average monthly values of the electricity demand, supply and import for the scenario 2: The PV power systems 2030

The average monthly values of the electricity produced by PV power systems is presented with a green curve, while the CEEP is presented with the yellow curve. The electricity demand of the IES is the same as in the business as usual 2030 scenario. The import of electricity from mainland was eliminated for all months excluding January and December, because the solar irradiation is relatively low during winter period. The import of electricity in January amounted to 333.06 MWh, while in December it amounted to 612.68 MWh. This scenario did not include battery storage capacities, so the surplus of the electricity produced by PV power systems in the amount of 13.57 GWh/year was considered as CEEP. The IES needs to implement the CEEP regulation strategy to match the electricity supply with the demand. The annual values of the electricity demand, import, supply and export are presented in Table 8.

Table 8. The individual annual values of the scenario 2: The PV power systems 2030

Scenario no.	2
Scenario name	The PV power systems 2030
Year	2030
Electricity demand [GWh/year]	18.04
Annual electricity production [GWh/year]	30.64
Import of electricity [GWh/year]	-0.95
CEEP [GWh/year]	13.57
Diesel-powered ferry transport demand [GWh/year]	6.55
Battery-Powered Electric Ferry demand [GWh/year]	0

According to the Alves et.al. [64] for the year 2030 the investment costs of the PV power systems were projected to be 640 €/kW, while the fixed operating and maintenance costs were assumed to be 1.7% of the investment costs and lifetime was 25 years. The PV power systems 2030 scenario annual investment costs were € 2,860,740.00. The annual costs are consisted of the electricity import costs, diesel consumption costs, CO_2 emission costs, maintenance costs and the annual investment costs, and their values are shown in Table 9.

Table 9. Annual costs of the IES for the scenario 2: The PV power systems 2030

Scenario no.	2
Scenario name	The PV power systems 2030
Cost type	Annual value
Import of electricity	124,740.00 €
Diesel-powered ferry transport fuel costs	750,000.00 €
CO_2 emission costs	314,000.00 €
Maintenance costs	601,000.00 €
Annual investment costs	1,066,000.00 €
Total	2,860,740.00 €

Further analysis of the results shows that 4% of the annual costs of the IES refer to the electricity import costs. The shares of other individual annual costs for the PV power systems 2030 scenario are shown in Figure 7.

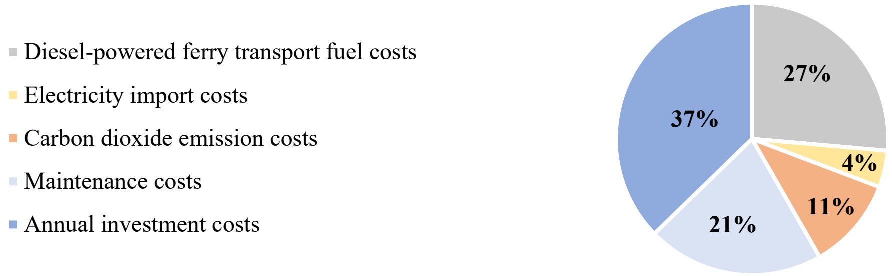

Figure 7. Share of the individual annual costs of the IES for the scenario 2: The PV power systems 2030

4.3. Scenario 3: The PV power systems and BEF 2030

The scenario 3 demonstrated the integration of the PV power systems and the implementation of the BEF into the IES of the Island of Cres for the year 2030. The installed capacities of the PV power systems in scenario 3 are equal to the capacities in scenario 2. Therefore, the electricity production was again 30.67 GWh/year. The conventional diesel-powered systems were replaced with battery-powered systems, so the ferry transport is 100% electric in the scenario 3. This resulted in shifting the demand of the ferry transport from the consumption of diesel fuel to the consumption of electricity for charging. The electricity demand of the 100%

electric ferry transport was 6.55 MWh/year. The electricity demand taken from the grid for charging the BEF was 7.28 MWh/year, due to efficiency of the grid to battery connection was assumed to be 90%. The total electricity demand of the IES increased by 40% compared to the scenario 2 and amounted to 25.33 GWh/year. The average monthly values of the electricity demand, import, export and CEEP for scenario 3 were obtained from the EnergyPLAN simulation (Figure 8).

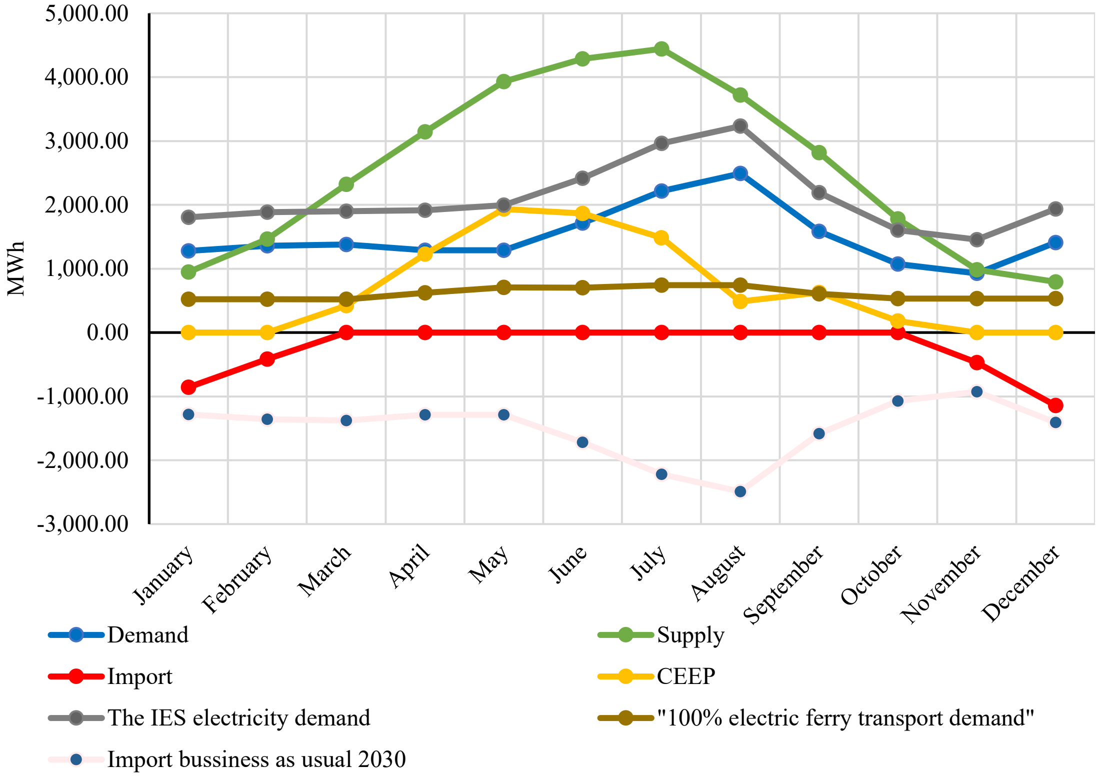

Figure 8. The average monthly values of the electricity demand, supply and import for the scenario 3: The PV power systems and BEF 2030

The total electricity demand of the IES is presented with the grey curve. The 100% ferry transport electricity demand (brown curve) is highest in July and August. This was expected, since ferries operate in high season mode and have increased daily number of round trips. The implementation of BEF required import of electricity in January in the amount of 856.44 MWh, in February in the amount of 416.51 MWh, in November in the amount of 470 MWh and in December in the amount of 1142.65 MWh. The CEEP in the scenario 3 was 8.23 GWh/year, so the CEEP is decreased by 39% compared to the scenario 2. The annual values of the electricity demand, supply, import, export and CEEP for the scenario 3 are shown in Table 10.

Table 10. The individual annual values for the scenario 3: The PV power systems and BEF 2030

Scenario no.	3
Scenario name	The PV power systems and BEF 2030
Year	2030
Electricity demand [GWh/year]	18.04
Annual electricity production [GWh/year]	30.64
Import of electricity [GWh/year]	-2.87
CEEP [GWh/year]	8.23
Diesel-powered ferry transport demand [GWh/year]	0
Battery-Powered Electric Ferry demand [GWh/year]	7.28

By implementing BEF into the IES, the diesel consumption and CO_2 emissions from the maritime transport were reduced to zero. The PV power systems and BEF 2030 scenario had total annual system costs of € 1,942,988.00. The annual system costs are shown in Table 11.

Table 11. Annual costs of the IES for the scenario 3: The PV power systems and BEF 2030

Scenario no.	3
Scenario name	The PV power systems and BEF 2030
Cost type	Annual value
Import of electricity	380,988.00 €
Diesel-powered ferry transport fuel costs	0.00 €
CO_2 emission costs	0.00 €
Maintenance costs	549,000.00 €
Annual investment costs	1,013,000.00 €
Total	1,942,988.00 €

Further analysis of the results shows that 20% of the annual costs of the IES refer to the electricity import costs. The shares of other individual annual costs for PV power systems 2030 integration scenario are shown in Figure 9.

Figure 9. Share of annual investment costs for the scenario 3: The PV power systems and BEF 2030

5. Conclusions

The integration of alternative technologies in different energy sectors is required to mitigate impacts of global warming and climate change. The integration of PV power systems is recognized as an alternative solution for achieving decarbonization of the power sector. The implementation of the BEF is presented as a convenient solution for achieving the electrification of the ferry transport and improving the grid stability through matching the electricity supply with the demand. The main findings of the analysis carried out are:

- The import of electricity from the mainland in the scenario 2 is reduced to zero by integrating planned PV power systems capacities into the IES.
- The annual electricity demand of the IES in scenario 2 requires approximately 59% of the annual electricity produced from the local PV power systems capacities. The 41% of the annual electricity produced from the local PV power systems is considered as CEEP. The IES requires integration of additional battery storage capacities.
- The method highlighted BEF as mobile battery storages that can reduce CEEP values by storing the electricity during periods of excess electricity production. The implementation of BEF decreased the CEEP in the scenario 3 by almost 40% compared to the CEEP in scenario 2.
- The implementation of BEF shifted programmable consumption from diesel fossil fuel to electricity. The CO_2 emissions from maritime transport were reduced to zero.
- The implementation of BEF decreased the annual costs of the IES by more than 30% compared to the annual costs of the IES scenario with the conventional diesel-ferry transport.

The implementation of the all-electric ferries powered with Li-ion batteries can achieve electrification of the selected voyages, since the departure schedules and voyage distances are convenient. However, more research that investigates S2G charging and discharging strategies is required to further reduce the CEEP. The synergy between the IES powered with different shares of RES and BEF should be further investigated with the life-cycle assessment and the life-cycle cost assessment. The approach of modelling synergies between the renewable-based power sector and the 100% electric ferry transport sector should be expanded by adding different RES in the IES, as well as investigating some other segments of the maritime transport that are convenient for electrification. Future research needs to be oriented towards modelling ferry smart charging strategies and exploring grid stabilization measures to further reduce the CEEP from the RES capacities.

Acknowledgements

This research was supported under the project Strengthening Transnational Co-operation, Knowledge and Technology Transfer in Development of Electric Vessels and Fostering Innovations in SME's (ZEVinnovation), (Project Index No. 2018-1-1185) funded by Iceland, Liechtenstein and Norway through the EEA and Norway Grants Fund for Regional Cooperation and conducted by the Center of Technology Transfer LLC (Croatia) together with the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture (Croatia).

REFERENCES

[1] Lee T, Glick MB, Lee JH. Island energy transition: Assessing Hawaii's multi level, policy-driven approach. Renew Sustain Energy Rev, 2020;118:109500.

[2] Papadis E, Tsatsaronis G. Challenges in the decarbonization of the energy sector. Energy, 2020;205:118025.

[3] European Comission. Energy. Topics. Markets and consumers. Clean energy for EU islands. https://ec.europa.eu/energy/topics/markets-and-consumers/clean-energy-eu-islands_en [accessed March 15, 2021].

[4] Smart Islands Initiative. The Smart Islands Declaration. https://www.smartislandsinitiative.eu/en/declaration.php [accessed March 15, 2021].

[5] Frazier AG, Brewington L. Current changes in alpine ecosystems of Pacific Islands. Encyclopedia of the World's Bimes. 2020; 607-619.

[6] Cosmi C, Dvarioniene J, Marques I, Di Leo S, Gecevičius G, Gurauskiene I, et al. A holistic approach to sustainable energy development at regional level: The RENERGY self-assessment methodology. Renew Sustain Energy Rev, 2015;49:693–707.

[7] European Comission. Climate Action. EU Action. Climate strategies & targets. 2030 climate & energy framework. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en [accessed October 27, 2021].

[8] European Parliament. Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Off J Eur Union, 2018;2018:82–209. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN [accessed March 22, 2022]

[9] European Comission. Proposal for a Regulation of the European Parliament and of the Council on the uptake of renewable and low-carbon fuels in maritime transport - FuelEU Maritime. https://www.transportenvironment.org/wp-content/uploads/2021/08/2021_06_FuelEU_Draft_proposal_leaked.pdf [accessed March 25, 2022]

[10] Helm C, Mier M. Steering the energy transition in a world of intermittent electricity supply: Optimal subsidies and taxes for renewables and storage. J Environ Econ Manage, 2021;109:102497.

[11] Charabi Y, Al Nasiri N, Al Awadhi T, Choudri BS, Al Bimani A. GHG emissions from the transport sector in Oman: Trends and potential decarbonization pathways. Energy Strateg Rev, 2020;32:100548.

[12] Vivek CM, Ramkumar P, Srividhya PK, Sivasubramanian M. Recent strategies and trends in implanting of renewable energy sources for sustainability - A review. Mater Today Proc, 2021;46:8204–8.

[13] Hoang AT, Pham VV, Nguyen XP. Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. J Clean Prod, 2021;305:127161.

[14] Mahmood D, Javaid N, Ahmed G, Khan S, Monteiro V. A review on optimization strategies integrating renewable energy sources focusing uncertainty factor – Paving path to eco-friendly smart cities. Sustain Comput Informatics Syst, 2021;30:100559.

[15] Fachrizal R, Shepero M, van der Meer D, Munkhammar J, Widén J. Smart charging of electric vehicles considering photovoltaic power production and electricity consumption: A review. ETransportation, 2020;4.

[16] Liu L, Senjyu T, Kato T, Howlader AM, Mandal P, Lotfy ME. Load frequency control for renewable energy sources for isolated power system by introducing large scale PV and storage battery. Energy Reports, 2020;6:1597–603.

[17] Graça Gomes J, Xu HJ, Yang Q, Zhao CY. An optimization study on a typical renewable microgrid energy system with energy storage. Energy, 2021;234.

[18] Ajanovic A, Hiesl A, Haas R. On the role of storage for electricity in smart energy systems. Energy, 2020;200:117473.

[19] Bertheau P. Supplying not electrified islands with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines. Energy, 2020;202:117670.

[20] Wang S, Tarroja B, Schell LS, Samuelsen S. Determining cost-optimal approaches for managing excess renewable electricity in decarbonized electricity systems. Renew Energy, 2021;178:1187–97.

[21] Mimica M, Krajačić G. The Smart Islands method for defining energy planning scenarios on islands. Energy, 2021;237.

[22] Alves M, Segurado R, Costa M. Increasing the penetration of renewable energy sources in isolated islands through the interconnection of their power systems. The case of Pico and Faial islands, Azores. Energy, 2019;182:502–10.

[23] Dominković DF, Bačeković I, Pedersen AS, Krajačić G. The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition. Renew Sustain Energy Rev, 2018;82:1823–38.

[24] Yuan M, Thellufsen JZ, Lund H, Liang Y. The electrification of transportation in energy transition. Energy, 2021;236.

[25] Bellocchi S, Gambini M, Manno M, Stilo T, Vellini M. Positive interactions between electric vehicles and renewable energy sources in CO2-reduced energy scenarios: The Italian case. Energy, 2018;161:172–82.

[26] Shi R, Li S, Zhang P, Lee KY. Integration of renewable energy sources and electric vehicles in V2G network with adjustable robust optimization. Renew Energy, 2020;153:1067–80.

[27] Hrnčić B, Pfeifer A, Jurić F, Duić N, Ivanović V, Vušanović I. Different investment dynamics in energy transition towards a 100% renewable energy system. Energy, 2021;237.

[28] Eurostat. Transport. Maritime transport. Maritime transport – short sea shipping – main annual results. https://ec.europa.eu/eurostat/databrowser/view/mar_sg_am_cw/default/table?lang=en [accessed October 25, 2021].

[29] Işıklı E, Aydın N, Bilgili L, Toprak A. Estimating fuel consumption in maritime transport. J Clean Prod, 2020;275:124142.

[30] García Reyes LE. Fourth IMO Greenhouse Gas Study. vol. 53. 2013.

[31] Atwoli L, H Baqui A, Benfield T, Bosurgi R, Godlee F, Hancocks S, et al. Call for emergency action to limit global temperature increases, restore biodiversity, and protect health. BMJ Case Rep, 2021;14:100274.

[32] Sui C, de Vos P, Stapersma D, Visser K, Ding Y. Fuel consumption and emissions of

ocean-going cargo ship with hybrid propulsion and different fuels over voyage. J Mar Sci Eng, 2020;8.

[33] International Maritime Organization (IMO). Media centre. IMO 2020 – cutting sulphur oxide emissions. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx [accessed October 27, 2021].

[34] Cullinane K, Bergqvist R. Emission control areas and their impact on maritime transport. Transp Res Part D Transp Environ, 2014;28:1–5.

[35] Bach H, Bergek A, Bjørgum Ø, Hansen T, Kenzhegaliyeva A, Steen M. Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. Transp Res Part D Transp Environ, 2020;87:102492.

[36] Fan A, Wang J, He Y, Perčić M, Vladimir N, Yang L. Decarbonising inland ship power system: Alternative solution and assessment method. Energy, 2021;226.

[37] Perčić M, Ančić I, Vladimir N. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector. Renew Sustain Energy Rev, 2020;131:110028.

[38] Wang H, Boulougouris E, Theotokatos G, Zhou P, Priftis A, Shi G. Life cycle analysis and cost assessment of a battery powered ferry. Ocean Eng, 2021;241:110029.

[39] Zubi G, Dufo-López R, Carvalho M, Pasaoglu G. The lithium-ion battery: State of the art and future perspectives. Renew Sustain Energy Rev, 2018;89:292–308.

[40] Perčić M, Frković L, Pukšec T, Ćosić B, Lun O, Vladimir N. Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. Energy, 2022;251:123895.

[41] European Maritime Safety Agency (EMSA). Electrical Energy Storage for Ships. http://www.emsa.europa.eu/publications/corporate-publications/download/6186/3895/23.html; 2020 [accessed November 3, 2020].

[42] Pfeifer A, Prebeg P, Duić N. Challenges and opportunities of zero emission shipping in smart islands: A study of zero emission ferry lines. eTransportation; 2020:100048.

[43] Freitas Gomes IS, Perez Y, Suomalainen E. Coupling small batteries and PV generation: A review. Renew Sustain Energy Rev, 2020;126:109835.

[44] EnergyPLAN. Advanced energy systems analysis computer model. https://www.energyplan.eu/ [accessed April 13, 2021].

[45] Šare A, Krajačić G, Pukšec T, Duić N. The integration of renewable energy sources and electric vehicles into the power system of the Dubrovnik region. Energy Sustain Soc, 2015;5.

[46] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy, 2008;36:3578–87.

[47] Development strategy of for the island of Cres for the period from 2015 to 2020. file:///C:/Users/lovro/Downloads/632%20(2).pdf [acessed April 15, 2022].

[48] Sustainable Energy Action Plan (SEAP) of the city of Cres until 2020. http://digarhiv.gov.hr/webpac-hidra-bib/?rm=results&f=SubjectIndexHR&v=obnovljiva%20energija%20003293&sort=1 [accessed April 20, 2021].

[49] Clean Energy for EU Islands. Cres-Lošinj archipelago. http://www.reakvarner.hr/sites/9192/upload/userfiles/publikacije/1580204180_creslos

inj_finaltransitionagenda_20191118_plan.pdf [acessed April 29, 2022
[50] European Commission. EU Reference Scenario 2016. Emergy, transport and GHG emissions. Trends to 2050. https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf [accessed April 29, 2022].
[51] European Comission. EU Science Hub. Photovoltaic Geographical Information System (PVGIS). https://ec.europa.eu/jrc/en/pvgis [accessed December 23, 2021].
[52] HEP d.d. HEP Group. https://www.hep.hr/about-hep-group/2502 [accessed December 20, 2021].
[53] Jadrolinija. Local ferry lines. https://www.jadrolinija.hr/o-nama/brodovi/trajekti/trajekti-lokalnih-linija [accessed April 13, 2021].
[54] Croatian Register of Shipping. Register of ships. https://www.crs.hr/hr/ [accessed April 26, 2022].
[55] The Agency for Coastal Liner Maritime Transport. Shipping schedules with price lists for 2022. Ferry line 332 Valbiska – Merag. https://agencija-zolpp.hr/wp-content/uploads/2019/04/332-Valbiska-Merag-2022_2.pdf
[56] The Agency for Coastal Liner Maritime Transport. Shipping schedules with price lists for 2022. Ferry line 334 Porozina – Brestova. https://agencija-zolpp.hr/wp-content/uploads/2019/04/334-Porozina-Brestova-2022_2.pdf
[57] Wu P, Bucknall R. Marine propulsion using battery power. Shipp Chang Clim Conf 2016, 2016:1–10.
[58] Liang Y, Zhao C, Yuan H, Chen Y, Zhang W, Huang J, et al. A review of rechargeable batteries for portable electronic devices. InfoMat, 2019;1:6–32.
[59] Iannaccone T, Landucci G, Tugnoli A, Salzano E, Cozzani V. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. J Clean Prod, 2020;260:121069.
[60] Zamiatina N. Comparative Overview of Marine Fuel Quality on Diesel Engine Operation. Procedia Eng, 2016;134:157–64.
[61] Gozillon D. Transport & Environment. FuelEU Maritime: T&E analysis and recommendations. https://www.transportenvironment.org/wp-content/uploads/2022/02/TE-Report-FuelEU-Maritime-1.pdf [acessed March 25, 2022]
[62] Christos B. Techno - economical feasibility study on the retrofit of double - ended Ro / Pax ferries into battery - powered ones Techno - economical feasibility study on the retrofit of double - ended Ro / Pax ferries into battery - powered ones. 2017.
[63] Urrutia C, Graichen J, Herold A. 2030 climate target plan: extension of European Emission Trading System (ETS) to transport emissions ENVI Workshop Proceedings. Policy Dep Econ Sci Qual Life Policies Dir Intern Policies, 2021.
[64] Alves M, Segurado R, Costa M. On the road to 100% renewable energy systems in isolated islands. Energy, 2020;198:117321.