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Optimal Charging and Discharging Strategies for Electric Cars in PV-BESS-Based Marina Energy Systems

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Abstract: The emerging concept of integrated community energy systems (ICESs) proves its suitability for improving the operation of local grids—increasing self-consumption from local generation, enhancing the load factor, and reducing energy cost. In Ballen marina—located on the Danish island of Samsø—the battery energy storage system (BESS)'s action can be possibly complemented by the flexibility of boats and electric cars. With the greater involvement of energy consumers, the energy system's performance may become more efficient—from both technical and economic perspectives. Within this framework, the optimal charging and discharging strategies of the marina's electric cars were developed and evaluated. The car usage profile was generated, utilising a stochastic approach to resemble daily variations in the driving pattern. The optimal charging strategy was established, subsequently integrating this action with boat flexibility. As a future scenario, the benefits of vehicle-to-grid (V2G) technology implementation were examined, proving significant enhancements of the future marina's grid—with increased photovoltaic (PV) generation capacity and the number of electric cars. The economic benefits of bidirectional charging were proven, with ample advantages for the marina and the rental company, leading to cost savings of up to 51.7% and minimising the energy export by 21.3%. Therefore, increasing the integration level of Ballen marina's flexible units—electric cars and boats—was concluded to be an important goal for the coming years.

Keywords: integrated community energy system; smart grid; demand–response; electric vehicles; battery energy storage system; smart island energy system

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1. Introduction

Local communities show high potential for the adaptation of smart multi-energy integration solutions [1]. The increasing number of electric vehicles (EVs) and flexible loads, along with small-scale generation and storage systems, enables individual households and companies to actively participate in local energy system operation. Their role continuously evolves—from passive consumers, through non-dispatchable prosumers, to active energy market players. In this context, ICESs are an advanced, intelligent approach for local multi-carrier integration [2]. The highly integrated local energy solutions are advantageous in terms of increasing system flexibility. With interconnected energy carriers, it is possible to better utilise emerging renewable energy resources (RESs). In this manner, the energy is produced and consumed locally, improving overall grid efficiency, managing grid bottlenecks, reducing dependency on the external system, and thus, possibly reducing energy costs [3,4]. Nevertheless, such integration requires several technical, socio-economic, and legislative solutions [5]. Along with energy conversion and storage techniques, expanding flexibility involves influencing consumers' behaviour, primarily via demand–response (DR) measures [6,7].

The integration of RESs into local power systems results in the need for increasing energy storage capabilities. Despite the rise in popularity of energy storage systems (ESSs) over the last few years, the investment cost is still substantial [8]. Within this framework, the solutions for widespread and low-cost storage techniques are essential. Considering the inevitable growth of the EV market share, smart EV charging and V2G technology become the prominent concepts to better utilise the potential of electric transport [9,10].

The concept of controlled charging schemes of EVs is receiving increased attention, redefining the functionality of electric means of transport. As a prospective part of this idea, V2G technology postulates employing the batteries of EVs for grid-oriented operation, providing active and reactive power support to the grid [9–11]. As the main principle, the discharging action is performed during peak hours, while recharging the battery during off-peak periods [12]. In this manner, the energy arbitrage is profitable for an EV owner, simultaneously benefiting the power system in several ways. The most-prominent advantages for the grid include RES exploitation, voltage and frequency support, power quality improvements, load levelling, and considerable environmental benefits [9,13]. Anticipating forthcoming smart grids, intelligent EV charging and V2G technology could become the fundamental components.

V2G technology is commonly investigated in the context of plug-in electric vehicles (PEVs), which can be divided into battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) [9]. It should be noted that the smart charging concept is not limited to electric cars only: all types of electric means of transport could be utilised for this purpose, with the implementation of adequate technological solutions [14]. In coastal locations, electric boats, ferries, and ships could be involved in supporting the operation of ICESs. In addition, participating in the V2G operation could benefit EV owners by enabling energy arbitrage possibilities or providing them with financial incentives. The profits should be sufficiently high to compensate for possible inconveniences, including possibly the accelerated degradation of the batteries and the inability to use EVs during certain periods [11].

Optimal management strategies for electric cars are an essential solution for increasing the efficiency of smart energy systems. Reference [15] proposed optimal charging strategies for decreasing power losses in the distribution grid. Minimising the operation cost is commonly chosen as the optimisation objective, as analysed in [16–21]. On the other hand, Reference [22] presented the optimal energy management strategy for a residential microgrid, integrating EVs, ESSs, and RES. Moreover, the bidirectional power flow capability of electric cars was taken into consideration in [23–25], proposing optimal V2G scheduling strategies. In addition, the battery degradation in EV scheduling optimisation was accounted for in [26,27].

This paper proposes the optimal charging and discharging strategies for electric cars in the ICES of Ballen marina on Samsø, comprising a PV plant, BESS, and other flexible loads—in the form of boats. The objective of the developed scheduling strategy was to increase the cost efficiency of energy usage for the marina and EV rental company, as well as to improve self-consumption from local PV generation. Moreover, the cooperation of smart car charging and boat flexibility was analysed, taking advantage of the marina's PV generation and BESS. In the future scenario, the impact of V2G technology implementation on the batteries' degradation was studied based on the employed battery ageing model. The optimisation model comprising the marina's generation, storage, electric cars, and boat flexibility was established, expanding the scope of previous research on marina energy systems [28–30]. The developed optimisation algorithm for the marina's energy management system—coordinating all the above-mentioned elements along with the battery degradation model—constitutes the novelty of this work.

The remainder of this paper is organised as follows. Section 2 outlines the essential parameters of Ballen marina's electric cars. The modelling of the electric car usage pattern and energy demand is performed in Section 3. Subsequently, Section 4 provides the methods used for this study. The simulation results of the analysed study cases are provided and discussed in Section 5. Finally, the conclusions and future works are presented in Section 6.

2. Electric Cars in Ballen Marina

Unquestionably, EVs are gradually replacing the conventional means of transport, equipped with environmentally unfriendly internal combustion engines [31]. Without adequate charging and management strategies, these vehicles can become an additional load on power systems, increasing peak power demand and resulting in the need for grid reinforcements. Nevertheless, EVs have proven to have a significant flexibility potential, which could be utilised and coordinated with other elements of ICESs. Therefore, the synergies between electric cars and the PV-BESS-based energy system of Ballen marina were investigated in this study, with the aim to determine the optimal management strategies, which can be utilised not only on Samsø, but also for other community energy systems. The outline of Ballen marina's energy system is presented in Figure 1.

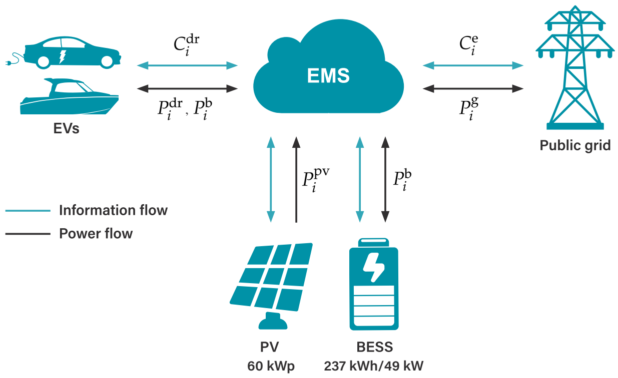

Figure 1. Marina's energy management system [30].

The docking boats constitute the main electrical load at Ballen marina, with the highest demand observable in summer. Furthermore, the marina's energy system comprises a 60 kWp PV plant and a 237 kWh/49 kW Li-ion BESS. In addition to these elements, electric cars also form an integral part of the smart energy system, especially during the summer period. The uniqueness of Ballen marina's energy system results from its seasonal electricity demand, combined with renewable generation, a storage system, and smart grid solutions. There are four EVs, out of which one is the Harbour Master's dedicated car (present all year round), and the remaining are rental cars that can be leased by sailors and other tourists [32–34]. The frequency of the rental cars' usage is typically high in the summer period. Furthermore, the rental company is considering the expansion of the business, placing four additional cars in the marina. The Harbour Master's vehicle is a Renault ZOE, assumed to be Model R110. On the other hand, the Volkswagen e-up! is the model of the rental cars, presumed to be produced in the years 2016–2019. It should be noted that rental cars are not available in the off-season period—from autumn to mid-spring—as the number of visiting sailors and tourists is significantly lower. The parameters of Ballen marina's electric cars are presented in Table 1 [35,36].

The unknown capacities of each model's battery were estimated based on the assumption of 90% accessible capacity. In this manner, the minimum and maximum state of charge (SOC) was assumed as, respectively, $SOC^{min} = 5\%$ and $SOC^{max} = 95\%$, with regard to the total EV's battery capacity [35,36]. Both types of cars support the three-phase AC Type 2 charging standard, which allows supplying the cars with AC power. Subsequently, AC power is converted by the on-board charger to DC, which is afterwards sent directly to the car's battery. Within this framework, the maximum AC charging power of EVs is limited by the capabilities of their internal on-board chargers [37,38].

Table 1. Parameters of electric cars at Ballen marina.

Parameter	Renault ZOE	Volkswagen e-up!
Total battery capacity (kWh)	45.6 [1]	18.7
Available battery capacity (kWh)	41	16.8 [1]
Range (km)	300	133
Efficiency (Wh/km)	137	126
Charging standard	Type 2	Type 2/CCS
Maximum AC charging (kW)	22	3.7
Maximum DC charging (kW)	–	40

[1] Estimated value.

Furthermore, the Volkswagen e-up! supports the Combined Charging System (CCS) standard, which allows significantly faster DC charging, bypassing the on-board charger. This way, the AC to DC conversion is performed at the off-board charging point [38]. For this car model, the maximum DC charging power is more than ten-times higher compared to the AC capabilities.

Currently, none of the aforementioned charging standards allow bidirectional charging, which is the basis for V2G technology's implementation. At the moment, CHAdeMO is the only standard supporting V2G capabilities [39]. Nevertheless, this charging method is being gradually phased out in Europe in favour of the CCS standard [40]. This situation inhibits the growth of V2G technology's real-life implementations.

Notwithstanding this, the CCS standard is expected to fully support bidirectional charging by 2025 [41]. Taking advantage of this functionality would require appropriate V2G charging points, supporting bidirectional AC–DC power conversion. In addition, EVs equipped with this charging port would need to be adapted for V2G participation from both the software and hardware perspectives.

Moreover, the Type 2 charging standard is also currently being investigated for its V2G potential. In this case, the EV's on-board charger is intended to provide the bidirectional power conversion, whereas the external AC charger is exempted from this requirement. Currently, Renault analyses this possibility through a demonstration programme, using the Renault ZOE model for this purpose [42].

Within this framework, the V2G capabilities of Ballen marina's electric cars were investigated only as a future scenario—taking into account also the possible increase in the number of EVs and PV capacity. Nonetheless, the implementation of this technology could be also beneficial for the marina's energy system to avoid increasing the maximum permissible power exchange with the public grid, which is challenging from the techno-economic perspective. At present, the maximum allowed import from the grid is equal to 86 kW, whereas the maximum export is limited to 49 kW [34]. Considering the present EV charging possibilities in the marina, four unidirectional three-phase 11 kW AC chargers for electric cars are currently deployed at the harbour. Thus, the maximum charging power of the Harbour Master's car (Renault ZOE) is limited to 11 kW, which is the rated power of the charger. In contrast, the rental cars (Volkswagen e-up!) can be charged with a maximum power of 3.7 kW, limited by their on-board chargers' properties.

Subsequently, the electric car demand at Ballen marina was modelled, taking into account the estimated EV usage patterns.

3. Modelling of Electric Car Demand

At Ballen marina, the car usage is considerably different from the typical residential usage patterns. The Harbour Master's car is used in his working hours, whereas the operation of the rental cars is associated with tourism. In general, the car usage pattern is irregular; nonetheless, the cars are typically not used during night hours [43]. Due to lack of recorded car usage data from the previous years, the EV demand was modelled based on the assumed typical daily usage. The undertaken daily driving pattern of the electric cars is shown in Table 2.

Table 2. Typical daily usage pattern of electric cars at Ballen marina.

Parameter	Harbour Master's	Rental 1	Rental 2	Rental 3
Departure time	08.00	10.00	12.00	14.00
Arrival time	17.00	18.00	15.00	17.00
Driven distance (km)	60	55	40	30
Energy usage (kWh)	8.2	6.9	5.0	3.8

Based on the assumed driven distance and efficiency presented in Table 1, the typical daily energy usage was calculated. In this context, the electric cars need to be supplied daily from the marina's grid with typically 23.9 kWh. In a real-life situation, the car usage pattern may look different every day. Therefore, a stochastic approach was employed for a better representation of EV usage. For this purpose, a probability density function was utilised, with the assumption of a normal distribution. The daily driven distance presented in Table 2 was taken as the mean value, whereas the standard deviation was assumed as $\sigma = 10$ km. Within this framework, the probability density function for each of the marina's electric cars is presented in Figure 2.

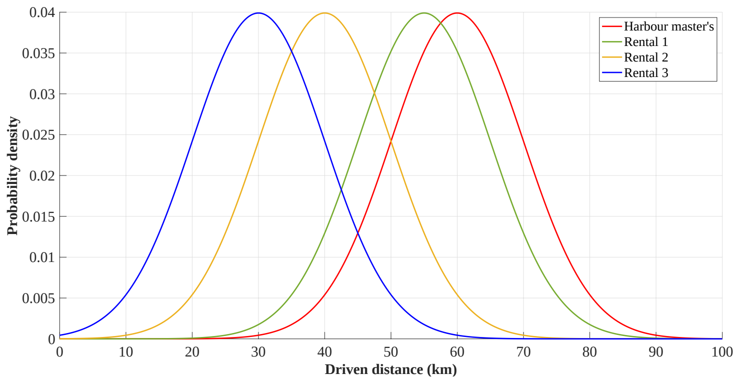

Figure 2. Probability density function for electric cars at Ballen marina.

Subsequently, the probability density function was utilised to generate a stochastic car usage pattern for each day of a summer week, with the highest electricity demand in a year. In this manner, a random daily driven distance for each car was generated, with the assumed mean value and standard deviation. If the generated distance differed by more than 10 km from the mean value, the departure or arrival hour was modified. In the case of an obtained distance greater than the mean value, either the departure time was advanced or the arrival time was postponed by one hour for every 10 km deviation. The decision between these actions was made in a random manner. Similarly, if the generated distance was smaller than the mean distance, either the departure time was postponed or the arrival time was advanced. Finally, the daily distance was equally distributed between the car usage hours. This way, a stochastic car usage pattern for an entire summer week was generated, as shown in Figure 3.

The generated car usage profile was utilised in the forthcoming simulations. In this study, a typical AC charging efficiency of $\eta^{b+} = 95\%$ was assumed [44]. Furthermore, the same value was used as a discharging efficiency η^{b-}—for the scenarios covering the V2G technology implementation. As the cars need to be ready for the next day's usage, they were restricted to be fully charged before 6.00.

The energy price for EV charging was assumed to be the same for all cars, under the assumption of the hourly varying marina's tariff—developed in [30]. In other words, the marina was assumed to not impose any additional margin on the rental company's electricity price. In this manner, the charging flexibility should be financially beneficial for both the marina and the rental company. Furthermore, the benefits from V2G participation should compensate for the possible inconvenience of cars' unavailability at certain hours.

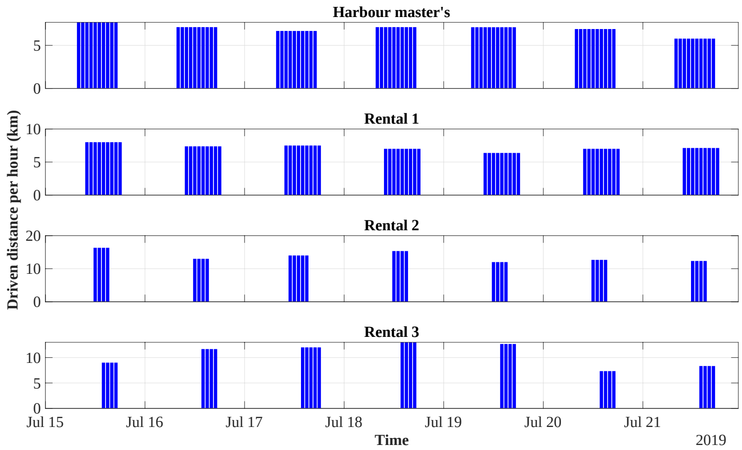

Figure 3. Generated electric car usage pattern.

Taking advantage of the popularity of Ballen marina among sailors, more rental electric cars are planned to be placed at the harbour. The marina currently expects four additional rental EVs, resulting in eight cars in total. For this reason, the harbour's energy system was ultimately investigated for the future scenario—with three-times increased PV capacity, boat flexibility, and eight cars participating in the V2G operation.

Further, the flexibility of the electric cars at Ballen marina was evaluated to determine the optimal charging and discharging patterns.

4. Proposed Optimal Operation of Marina's Energy System

The simulations were carried out for a summer week (15–21 July 2019)—when the marina's load is highest due to the peak tourist season and rental cars are frequently used. The analysis was conducted based on the recorded boat demand of the marina from 2019, presented along with the PV generation data in [30]. The following study cases were taken into consideration:

- Optimal charging strategy;
- Electric cars and boat flexibility;
- Bidirectional power flow;
- Future scenario.

Despite the simulation time being limited to only one week, the proposed study cases comprised the three main operation regimes of the marina's energy system:

- Excess of PV generation;
- Shortage of PV generation;
- Approximate sufficiency of PV generation.

Firstly, the optimal charging strategy was developed, utilising mixed-integer linear programming optimisation. In this scenario, the cooperation of EVs with the BESS was analysed, investigating the EVs' impact on the marina's grid. The optimal charging was compared with the baseline scenario, in which cars are charged immediately upon their arrival at the harbour. Subsequently, the model was enhanced with boat flexibility, with the aim to coordinate the operation of the entire marina's ICES—extending the DR action presented in [30]. Further, the benefits from future V2G technology implementation were evaluated, developing the optimal strategy for bidirectional power flow between electric cars and the marina's grid. As this study case considered the prospective configuration of the marina's ICES, the PV capacity was assumed to be three-times increased (from 60 kWp to 180 kWp)—since the existing PV plant size was proven to be too small, based on the results of [45]. Ultimately, the future scenario with eight electric cars and the V2G technology was analysed.

In principle, the flexibility of electric cars and boats is equivalent to adding more BESS capacity—in terms of enabling the integration of more renewable energy. Nonetheless, due to the significant nonlinearities of the actual ICES of Ballen marina—such as the capacity limits of smaller batteries and their limited charging power—a more complex calculation approach was necessary, intending to achieve more realistic results. Taking this into consideration, the developed stochastic model was based on the individual components—cars and boats—leading to a better representation of the marina's energy system. From the point of view of the electrical grid, there are many similarities between electricity demand from electric cars and boats, primarily due to the application of constant current and constant voltage charging algorithms [46]. Nevertheless, in the proposed optimisation algorithm, the boat demand was aggregated—as a result of the lower controllability of these units for the optimal energy management schemes.

For the EV coordination simulations, the battery model developed in [45]—along with the battery degradation model presented in [47]—was utilised, serving as the equality and inequality constraints for the optimisation model:

$$\eta^{\mathrm{b}+} = \eta^{\mathrm{b}-} = \sqrt{\eta^{\mathrm{b}}} \tag{1}$$

$$SOC_i = SOC_{i-1} + \left(P_i^{\mathrm{b}+}\eta^{\mathrm{b}+} - P_i^{\mathrm{b}-}/\eta^{\mathrm{b}-}\right)\tau / E_{i-1}^{\mathrm{b\,max}} \tag{2}$$

$$E_i^{\mathrm{b+max}} = E_{i-1}^{\mathrm{b\,max}}\left(SOC^{\mathrm{max}} - SOC_{i-1}\right)/\eta^{\mathrm{b}+} \tag{3}$$

$$E_i^{\mathrm{b-max}} = E_{i-1}^{\mathrm{b\,max}}\left(SOC_{i-1} - SOC^{\mathrm{min}}\right)\eta^{\mathrm{b}-} \tag{4}$$

$$0 \le P_i^{\mathrm{b}+} \le \delta_i^{\mathrm{b}+} E_i^{\mathrm{b+max}}/\tau \tag{5}$$

$$0 \le P_i^{\mathrm{b}-} \le \delta_i^{\mathrm{b}-} E_i^{\mathrm{b-max}}/\tau \tag{6}$$

$$\delta_i^{\mathrm{b}+}, \delta_i^{\mathrm{b}-} \in \{0,1\} \tag{7}$$

$$\delta_i^{\mathrm{b}+} + \delta_i^{\mathrm{b}-} \le 1 \tag{8}$$

$$P_i^{\mathrm{b}+}, P_i^{\mathrm{b}-} \le P^{\mathrm{b\,max}} \tag{9}$$

$$P_i^{\mathrm{b}} = P_i^{\mathrm{b}+} - P_i^{\mathrm{b}-} \tag{10}$$

$$\xi^{\mathrm{bf,\,cal}} = 0.1723 \cdot \mathrm{e}^{0.007388 \cdot SOC}\left(\frac{t}{732}\right)^{0.8} \tag{11}$$

$$\xi^{\mathrm{bf,\,cyc}} = 0.021 \cdot \mathrm{e}^{-0.01943 \cdot SOC^{\mathrm{mean}}} DOD^{0.7162} k^{0.5} \tag{12}$$

$$\xi^{\mathrm{bf}} = \xi^{\mathrm{bf,\,cal}} + \xi^{\mathrm{bf,\,cyc}} \tag{13}$$

$$E_i^{\mathrm{b\,max}} = E_{i=0}^{\mathrm{b\,max}}\left(1 - \xi^{\mathrm{bf}}\right) \tag{14}$$

where:

$\eta^{\mathrm{b}+}/\eta^{\mathrm{b}-}$	Battery charging/discharging efficiency;
η^{b}	Battery round-trip efficiency;
i	Index of time slot;
SOC_i	Battery state of charge;
$P_i^{\mathrm{b}+}/P_i^{\mathrm{b}-}$	Battery charging/discharging power;
τ	Time step size;
$E_i^{\mathrm{b\,max}}$	Battery capacity;
$E_i^{\mathrm{b+max}}/E_i^{\mathrm{b-max}}$	Battery maximum charging/discharging rate;
$SOC^{\mathrm{max}}/SOC^{\mathrm{min}}$	Battery maximum/minimum state of charge;
$\delta_i^{\mathrm{b}+}/\delta_i^{\mathrm{b}-}$	Battery charging/discharging binary decision variable;
$P^{\mathrm{b\,max}}$	Battery maximum power;
P_i^{b}	Battery power;
$\xi^{\mathrm{bf,\,cal}}$	Battery calendar ageing;
t	Idling time;
$\xi^{\mathrm{bf,\,cyc}}$	Battery cycle ageing;
SOC^{mean}	Mean battery state of charge during cycle;

DOD	Battery depth of discharge;
k	Number of battery cycles;
ξ^{bf}	Total battery capacity degradation.

For Ballen marina's BESS, a typical round-trip efficiency of $\eta^{\mathrm{b}} = 95\%$ was assumed. In addition, the minimum and maximum SOC was limited by, respectively, $SOC^{\min} = 2.5\%$ and $SOC^{\max} = 97.5\%$. [30]

Further, the power exchange with the utility grid was modelled as in [45]:

$$0 \leq P_i^{\mathrm{g}+} \leq \delta_i^{\mathrm{g}+} P^{\mathrm{g}+\max} \tag{15}$$

$$0 \leq P_i^{\mathrm{g}-} \leq \delta_i^{\mathrm{g}-} P^{\mathrm{g}-\max} \tag{16}$$

$$\delta_i^{\mathrm{g}+}, \delta_i^{\mathrm{g}-} \in \{0, 1\} \tag{17}$$

$$\delta_i^{\mathrm{g}+} + \delta_i^{\mathrm{g}-} \leq 1 \tag{18}$$

$$P_i^{\mathrm{g}} = P_i^{\mathrm{g}+} - P_i^{\mathrm{g}-} \tag{19}$$

where:

$P_i^{\mathrm{g}+} / P_i^{\mathrm{g}-}$	Power import/export from/to the grid;
$\delta_i^{\mathrm{g}+} / \delta_i^{\mathrm{g}-}$	Power import/export binary decision variable;
$P^{\mathrm{g}+\max} / P^{\mathrm{g}-\max}$	Maximum power import/export;
P_i^{g}	Power exchange with the grid.

To prevent energy arbitrage from batteries—understood as selling energy back to the public grid—an additional constraint was introduced, precluding simultaneous battery discharging and energy export actions:

$$\delta_i^{\mathrm{b}-} + \delta_i^{\mathrm{g}-} \leq 1 \tag{20}$$

Consequently, the power balance equality constraint was formulated:

$$P_i^{\mathrm{l}} + P_i^{\mathrm{b}} - P_i^{\mathrm{g}} - P_i^{\mathrm{pv}} = 0 \tag{21}$$

where:

P_i^{l}	Marina's electrical load;
P_i^{pv}	PV production.

For the scenarios including boat flexibility, the flexibility model presented in [30] was adopted, representing constraints on DR from flexible consumption:

$$P_i^{\mathrm{dr}} = P_i^{\mathrm{l}} + P_i^{\mathrm{dr}+} - P_i^{\mathrm{dr}-} \tag{22}$$

$$0 \leq P_i^{\mathrm{dr}+} \leq \delta_i^{\mathrm{dr}+} \left(\overline{P^{\mathrm{l}}} - P_i^{\mathrm{l}}\right) \lambda^{\mathrm{dr}} \tag{23}$$

$$0 \leq P_i^{\mathrm{dr}-} \leq \delta_i^{\mathrm{dr}-} \left(P_i^{\mathrm{l}} - \overline{P^{\mathrm{l}}}\right) \lambda^{\mathrm{dr}} \tag{24}$$

$$\delta_i^{\mathrm{dr}+}, \delta_i^{\mathrm{dr}-} \in \{0, 1\} \tag{25}$$

$$\delta_i^{\mathrm{dr}+} + \delta_i^{\mathrm{dr}-} \leq 1 \tag{26}$$

$$\sum_{i=1}^{\mathscr{H}} P_i^{\mathrm{dr}} = \sum_{i=1}^{\mathscr{H}} P_i^{\mathrm{l}} \tag{27}$$

$$P_i^{\mathrm{dr}} + P_i^{\mathrm{b}} - P_i^{\mathrm{g}} - P_i^{\mathrm{pv}} = 0 \tag{28}$$

where:

P_i^{dr}	Demand–response power;
$P_i^{\mathrm{dr}+} / P_i^{\mathrm{dr}-}$	Increase/decrease in demand–response power;
$\delta_i^{\mathrm{dr}+} / \delta_i^{\mathrm{dr}-}$	Demand–response power increase/decrease binary decision variable;
$\overline{P^{\mathrm{l}}}$	Mean load over time horizon;
λ^{dr}	Flexibility factor;
$\mathscr{H}$	Time horizon.

As introduced in [30], a 24 h time horizon—starting at 12.00—was used. The optimisation objective was to minimise the overall energy cost, coordinating the EV charging and discharging action with the BESS and—in the last three scenarios—boat flexibility. Hence, the following optimisation problem was employed, extending the number of decision variable sets—from one (dedicated to only the BESS) to five (BESS and electric cars):

$$\begin{aligned} \text{minimise} \quad & \sum_{i=1}^{\mathscr{H}} \left(P_i^{\mathrm{g}+} C_i^{+} - P_i^{\mathrm{g}-} C_i^{-} \right) \\ \text{subject to:} \quad & (5)\text{–}(9), (15)\text{–}(18), (20), (21) \end{aligned} \tag{29}$$

where C^{+}/C^{-} denotes the marina's energy buying/selling price.

For each electric car, the battery degradation was included in the calculations, based on the presented ageing model. In the case of scenarios including boat flexibility, the optimisation problem—additionally including sailors' DR and its corresponding constraints—is formulated as

$$\begin{aligned} \text{minimise} \quad & \sum_{i=1}^{\mathscr{H}} \left(P_i^{\mathrm{dr}} C_i^{\mathrm{dr}} + P_i^{\mathrm{g}+} C_i^{+} - P_i^{\mathrm{g}-} C_i^{-} \right) \\ \text{subject to:} \quad & (5)\text{–}(9), (18)\text{–}(23), (20), (28) \end{aligned} \tag{30}$$

where C_i^{dr} denotes the energy price for sailors in the demand–response scheme.

For the scenarios without the V2G technology, the bidirectional power flow was prevented by setting the battery discharging binary decision variable to be inactive, as $\delta_i^{\mathrm{g}-} = 0$. Furthermore, in the study cases with increased PV capacity, the additional term was added to the objective function, preventing excessive energy export. This way, the optimisation objective was to minimise the energy cost for the marina and sailors, as well as to avoid energy export:

$$\begin{aligned} \text{minimise} \quad & \sum_{i=1}^{\mathscr{H}} \left(P_i^{\mathrm{dr}} C_i^{\mathrm{dr}} + P_i^{\mathrm{g}+} C_i^{+} + P_i^{\mathrm{g}-} \left(1 - C_i^{-}\right) \right) \\ \text{subject to:} \quad & (5)\text{–}(9), (15)\text{–}(18), (20), (23)\text{–}(28) \end{aligned} \tag{31}$$

In the initial scenario, the baseline charging strategy was compared with the developed optimal charging pattern. In the baseline strategy, the electric cars were fully charged right after they arrived at the marina. Within this framework, the batteries of the EVs should reach the $SOC^{\max}$ level as soon as possible, taking into account the maximum charging power. The marina's BESS was scheduled in the most-cost-efficient way, utilising the optimisation problem (29).

Developing the optimal charging strategy, the electric cars should be charged in the most-cost-efficient way, taking into account the hourly varying electricity pricing for the marina. As mentioned in Section 3, the EVs were restricted to be fully charged before 6.00. Moreover, the cars were obliged to have full batteries at the end of the simulation period—to ensure a fair comparison with the baseline strategy. The flowchart of the optimal charging strategy—which applied to each of the marina's EVs—is presented in Figure 4.

With the aim to integrate EVs into energy systems to a greater extent, the V2G technology is widely considered a feasible and effective solution [11]. At Ballen marina, the bidirectional power flow between EVs and the grid could cooperate with the local BESS, overcoming its deficiencies. Considering the plans of increasing PV capacity at Ballen marina, the BESS capabilities may be insufficient to minimise energy export to a satisfactory degree. In the scenarios with bidirectional power flow, EVs could be used as a buffer for the excess PV generation instead of investing additional resources for increasing the BESS's capacity.

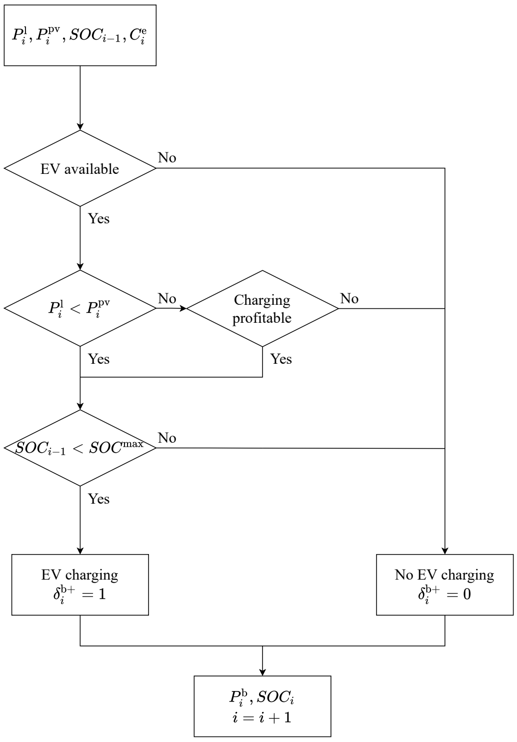

Figure 4. Optimal charging strategy flowchart.

For the analysed week, PV excess did not occur—taking into account the presently installed PV plant. Within this framework, the PV capacity increased three times for the purpose of this study case: from 60 kWp to 180 kWp. This way, the benefits of the V2G technology implementation can be easily identified, being also valuable for other local power systems with excess renewable generation.

The optimisation problem (31) was employed to determine the optimal integrated operation of the marina's ICES—including BESS action, bidirectional car charging, and boat flexibility. The binary state of the decision variables was determined by the optimisation algorithm, with the assumption of converging input conditions. The flowchart of this operation—with the input and output parameters for each time slot—is shown in Figure 5.

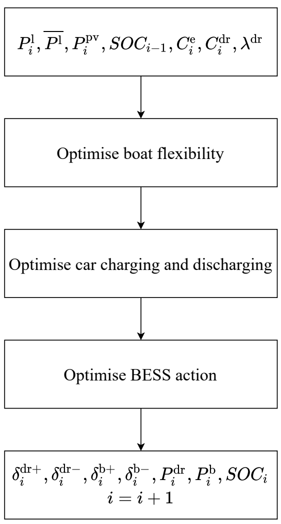

Figure 5. Optimal ICES operation flowchart.

To ensure the benefits of the V2G implementation for both the marina and the rental company, an appropriate pricing scheme needs to be proposed. In the scenarios without the V2G technology, the rental company was assumed to be billed based on the hourly varying tariff [30]. Nonetheless, the marina's PV generation did not affect the EV charging price. With the V2G technology implementation, a greater level of integration between rental cars and the marina is required. Within this framework, the V2G action should be advantageous for both involved parties, ensuring better utilisation of local generation and, therefore, possibly improved cost efficiency for the marina and the rental company. For these reasons, the following assumptions were adopted in the scenarios with bidirectional power flow:

- As the implementation of the V2G technology requires a greater level of flexibility and engagement on the demand side, the EVs were restricted to be fully charged no longer than one hour before their planned departure time—instead of being fully charged before 6.00.
- Allowing the marina to use rental EVs for bidirectional power flow, the rental company would be permitted to use excess PV generation to charge the electric cars for free.
- During the instances of no surplus production, the rental company would pay the standard energy price based on the Elspot tariff.
- No additional benefits would be provided to the rental company for the discharged energy.

Subsequently, the results of the performed simulations are outlined and discussed.

5. Results and Discussion

In this section, the simulation results are presented and compared to identify the most-beneficial scenario for the marina's grid operation.

5.1. Optimal Charging Strategy

Firstly, the results of the baseline and optimal charging strategies—with charging power and SOC—are presented in Figure 6.

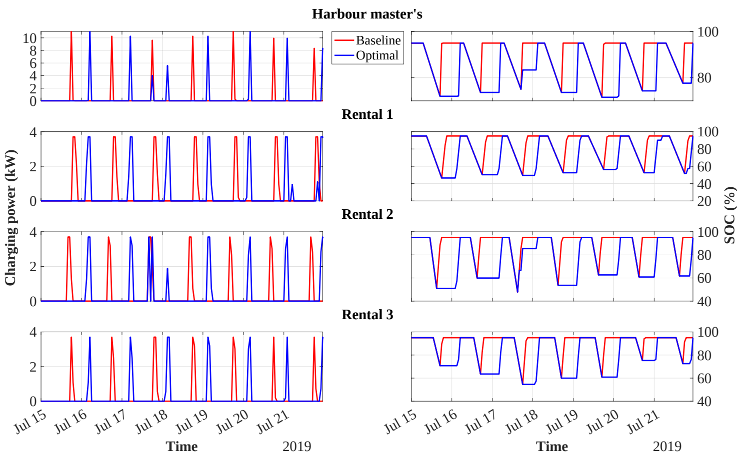

Figure 6. Baseline and optimal car charging strategies.

Considering the baseline strategy, it was observed that the cars were typically charged during the afternoon peak. Since the Harbour Master's EV has a higher maximum AC charging capability, the charging power reached higher values—compared to the rental cars. Despite the highest average daily driven distance, this car is typically fully charged in only one hour. On the other hand, the rental cars' charging action takes no more than three hours.

Nonetheless, the baseline EV charging pattern was not efficient and left room for further improvements. First of all, the charging action increased the afternoon peak demand, which is adverse in terms of power losses and the daily load factor, understood as the ratio of the mean load to the peak demand. Moreover, the afternoon Elspot prices are typically relatively high, which makes the EV charging action sub-optimal during this period. Therefore, the optimal charging strategy was developed with the aim to mitigate these inefficiencies.

With the optimal charging pattern, the EVs were charged during the periods of the lowest Elspot prices. Typically, the charging action is performed during the night, between 3.00 and 5.00. The exception to this was 17 July, when the energy prices were low during the afternoon hours.

For both strategies, the BESS installed at the marina site acted in the same way, as presented in Figure 7.

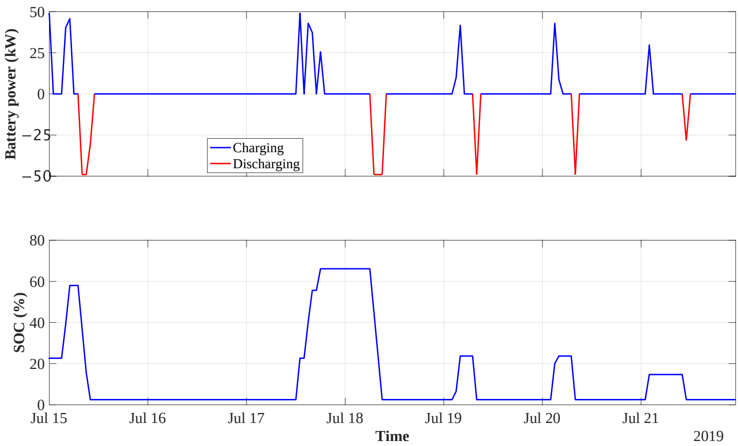

Figure 7. Optimal battery operation.

Since the PV generation was smaller than the load for the entire simulation week, the battery cannot act as a buffer for the excess PV production. Instead, the battery pre-charges from the public grid during periods of low prices and, subsequently, discharges during peak price hours. Thereafter, the marina's load profiles—including boat and EV demand—for the baseline and optimal charging strategies are presented in Figure 8.

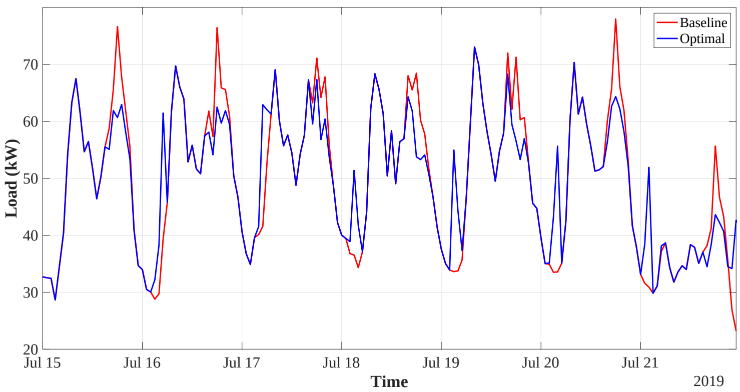

Figure 8. Marina's load for different car charging strategies.

With the optimal charging strategy, electric cars are charged during the most-cost-efficient periods of the day. Besides the imminent cost savings, this action also affects the overall loading of the marina's grid. It was observed that the optimal strategy effectively reduced the afternoon peak demand while increasing the consumption during night hours—as, for instance, seen on 20 July. Therefore, this charging pattern can be concluded as more efficient for the marina's energy system, taking into account the benefits of peak shaving and valley filling. Subsequently, the smart EV charging strategy and boat flexibility were integrated, evaluating the advantages for all involved parties.

5.2. Electric Cars and Boats' Flexibility

The Ballen marina's community energy system may benefit from a proper integration of all its primary components. For this reason, the cooperation of the marina's PV generation, BESS, boat demand, and electric cars was investigated in this scenario. The scheduling of electric cars and boats was performed using the optimisation problem (30), with the flexibility factor of $\lambda^{\mathrm{dr}} = 50\%$—serving as a parameter constraining the maximum load shifting action. The assumption of $\lambda^{\mathrm{dr}} = 50\%$ resulted in a realistic load profile, which is likely to be achieved in real-life smart grid implementations. The sensitivity analysis of the flexibility factor can be found in [30].

The resulting EV charging profile was the same as the optimal charging strategy presented in Figure 6, with only negligible changes. Moreover, the BESS action was similar to that in Figure 7. The obtained marina's load profile is presented in Figure 9, along with the comparison to the scenario without boat flexibility.

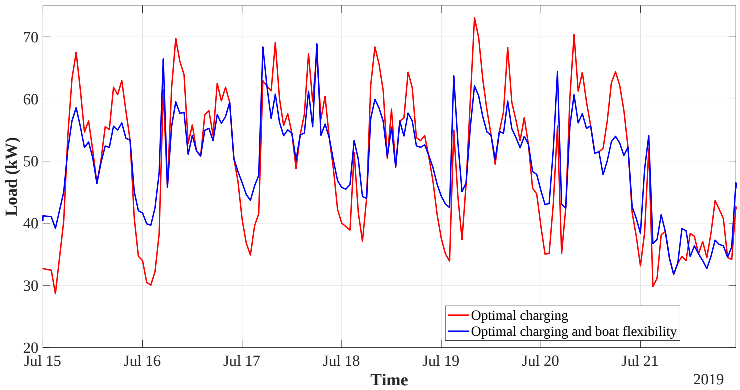

Figure 9. Marina's load with optimal car charging and boat flexibility.

Since the arriving boats constitute the most-significant load for the marina, their flexibility had a bigger impact on the load profile's shape compared to the optimal EV charging strategy. Nonetheless, the integration of both EV smart charging and boat flexibility resulted in the most-improved demand profile. Further, the simulation results of the three analysed scenarios were quantified and outlined in Table 3.

Table 3. Simulation results for optimal charging strategy and boat flexibility for a week.

Parameter	Case		
	Baseline	**Optimal Charging**	**With Boat Flexibility**
Load factor (%)	64.0	68.3 (+6.7%)	72.5 (+13.3%)
Marina's energy cost (EUR)	1302	1301 (−0.1%)	1298 (−0.3%)
Harbour Master's cost (EUR)	13.5	13.1 (−3.0%)	13.1 (−3.0%)
Rental company's cost (EUR)	29.3	28.6 (−2.4%)	28.6 (−2.4%)
Sailors' energy cost (EUR)	2726	2726	2663 (−2.3%)

Analysing the results, the weekly load factor was unaffected by the optimal charging strategy as the morning demand peaks were higher than the afternoon ones. Nonetheless, the integration of boat flexibility increased this parameter by 13.3%, significantly improving the marina's grid operation. In this manner, the peak shaving action can prevent any potential undervoltages in the local grid, which may occur on the long piers connecting the boats. In contrast, the cost savings for the marina were marginal, with, respectively, 0.1%

and 0.3% savings for the scenarios without and with boat flexibility. It should be noted that the presented marina's energy cost is related to the combined cost of supplying boats and all the electric cars. In this case, sailors and the rental company would be required to pay for their energy usage at the marina.

The optimal charging strategy reduced the charging cost for both Harbour Master's car and rental company, leading to, respectively, 3.0% and 2.4% savings. On the other hand, the energy cost for sailors decreased only in the scenario with boat flexibility, corresponding to a 2.3% savings.

The benefits from the optimal charging of the marina's EVs were noticeable, demonstrating improvements compared to the baseline scenario. Nevertheless, electric cars could be integrated in the future along with the V2G technology, enabling bidirectional power flow between their batteries and the marina's grid. Thus, this innovative approach was investigated in the forthcoming scenarios.

5.3. Bidirectional Power Flow

Consequently, the resulting optimal charging and discharging strategy for all marina's electric cars is presented in Figure 10.

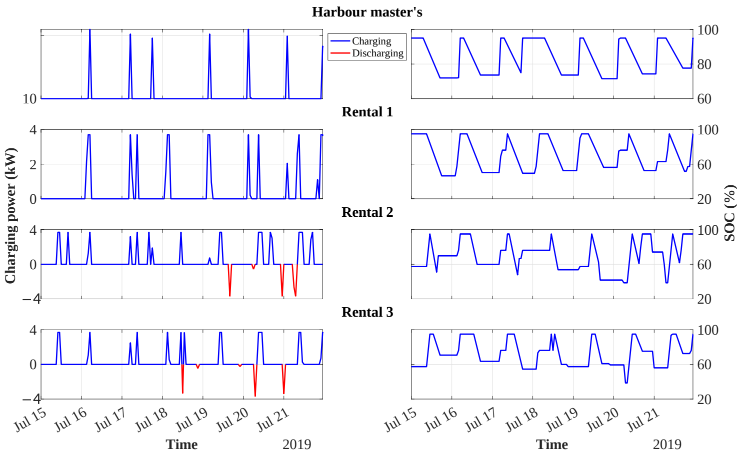

Figure 10. Optimal bidirectional power flow strategy.

With increased PV capacity, the charging action was typically performed during the periods of PV excess—either in the morning or in the afternoon. Furthermore, during the second half of the week—when PV generation was higher—the EVs performed the V2G action, bidirectionally exchanging energy with the marina's grid. Since the Harbour Master's car and the first rental car are normally used until the late evening hours, they do not participate in the bidirectional power flow. In this case, charging from PV excess and discharging in the later hours was not feasible, as the cars were unavailable during the sunny hours. Nevertheless, the other two rental cars participated in the V2G action.

Further, the total load of the marina and the BESS action are presented in Figure 11.

The marina's load profile was considerably levelled out by the boat flexibility. The peak demand was observed on 20 July, reaching more than 72 kW. Nonetheless, it was entirely covered by the PV production, with the excess being used for BESS charging. The batteries' utilisation was 41.1%, which is more than three-times higher than the utilisation in the previous scenarios (13.1%) presented in this study. The greater utilisation of the existing BESS is one of the technical goals for the marina, which can be achieved by the installation of additional PV units, as proven in this scenario.

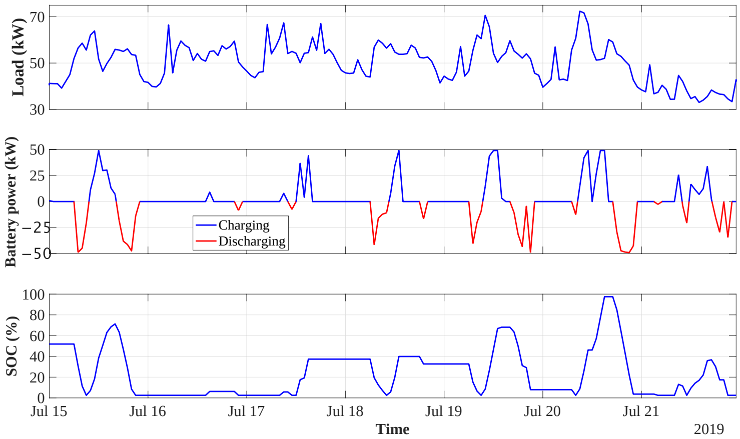

Figure 11. Marina's load and BESS with bidirectional power flow strategy.

The commonly expressed concerns regarding the V2G technology implementation relate to the possible situation of accelerated battery ageing. For this reason, the battery degradation of the marina's EVs was evaluated, based on the ageing model presented in [45]. The weekly battery degradation of electric cars—without and with the V2G technology—is presented in Table 4.

Table 4. Weekly battery degradation of electric cars.

Car Ageing (%)	No V2G			With V2G		
	Calendar	Cycle	Total	Calendar	Cycle	Total
Harbour Master's	0.09	0.00	0.09	0.08	0.01	0.09
Rental 1	0.08	0.01	0.09	0.07	0.01	0.08
Rental 2	0.11	0.01	0.12	0.10	0.01	0.11
Rental 3	0.11	0.00	0.11	0.11	0.01	0.12

It is clearly seen that the main EV battery degradation mode was calendar ageing. Since the cars are mostly parked—waiting for use while being fully charged—their batteries are idling at a high SOC level for many hours in a day. Furthermore, the battery degradation due to calendar ageing is several times higher than the cycle ageing mode—related to the car usage and charging action.

With bidirectional power flow, the employed battery model indicates decreased total battery ageing of two rental cars, extending the lifetime of these vehicles. The greater utilisation of batteries increased the cycle ageing mode; nevertheless, the calendar ageing was decreased by a higher factor. Thus, the model signifies lower battery degradation if the car is participating in the V2G operation, which is in line with the findings in [48]. Within this framework, participating in bidirectional charging would have twofold benefits for the rental company, improving the cost efficiency and the lifetime of the EVs. The total battery degradation of the two remaining cars (the Harbour Master's car and the third rental car) was either unaffected or affected negatively. Nevertheless, there is still no consensus on the effect of the V2G implementation on battery health [49]. Some studies suggested that bidirectional charging has no significant impact on the battery's lifetime [50,51], whereas other research implies that the V2G action may accelerate battery degradation [52].

Ultimately, the marina's grid operation was evaluated for the future scenario, with the anticipated increase in the number of EVs.

5.4. Future Scenario

In this scenario, four additional electric cars were assumed to be placed in the marina. The anticipated new EVs were assumed to be identical to the existing rental cars (Volkswagen e-up!). Furthermore, their usage pattern was modelled with a similar approach as in Section 3. The typical daily usage pattern of Rental Car 4 was assumed the be the same as the first rental car's; Rental Cars 5 and 7 have the same normal usage as the second car; Rental Car 6 is identical to the third EV. Within this framework, a stochastic car usage pattern for the eight EVs at the marina—based on the probability density function—was generated and presented in Figure 12.

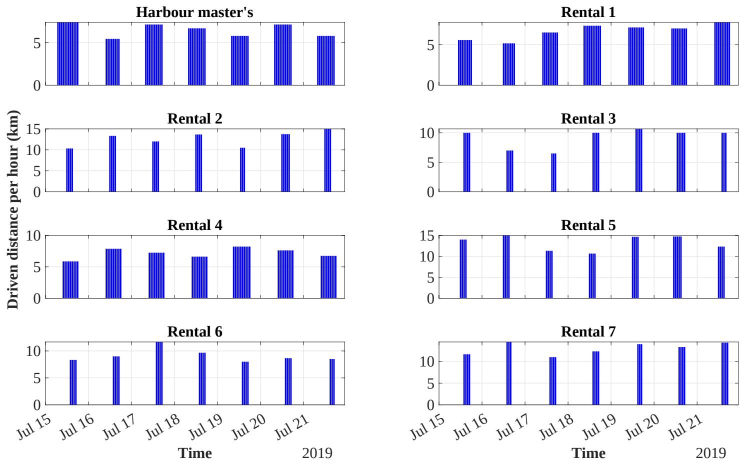

Figure 12. Generated electric car usage pattern for the eight cars.

Thereafter, the generated usage pattern was utilised to determine the optimal operation of the marina's grid, with the same constraints and objective function as in the previous scenario. The optimal bidirectional power flow strategy for the future scenario is shown in Figure 13.

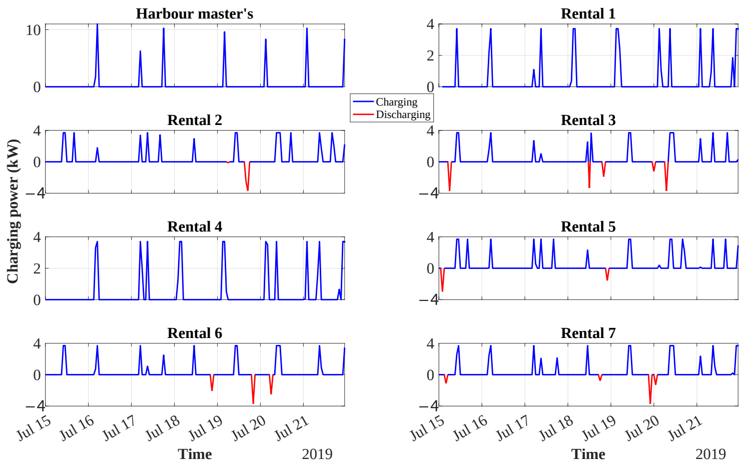

Figure 13. Optimal bidirectional power flow strategy for the future scenario.

It was observed that five out of the eight cars at the marina support the local grid with the V2G operation. For the remaining three cars, this action was not beneficial due to the cars' unavailability for typically eight to nine hours per day. Similar to the previous scenario, most of the cars' discharging action was performed during the second half of the week, when PV generation was higher. Further, the marina's load and BESS action are presented in Figure 14.

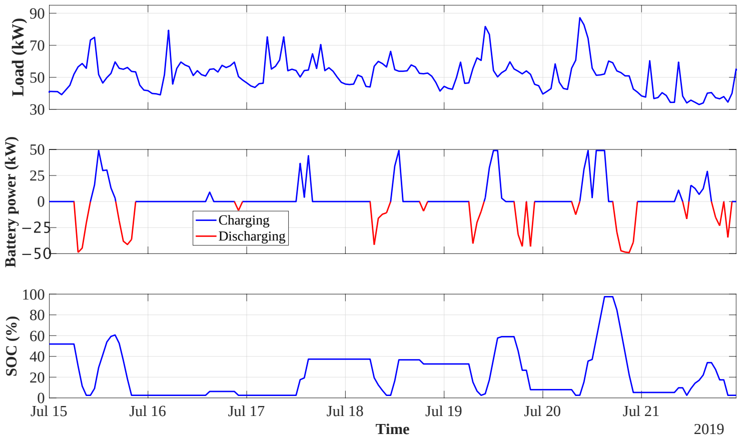

Figure 14. Marina's load and BESS for the future scenario.

The marina's peak load exceeded 87 kW; however, it was fully supplied by the local PV generation. The BESS utilisation was 35.1%, coordinating its operation with the bidirectional power flow from the EVs and boat flexibility. Finally, the potential benefits from the V2G technology implementation—for four and eight cars—were quantified and presented in Table 5.

Table 5. Simulation results for bidirectional power flow with increased PV capacity.

Parameter	Four Cars		Eight Cars	
	No V2G	With V2G	No V2G	With V2G
Energy import (kWh)	4105	4079 (−0.6%)	4 271	4218 (−1.2%)
Energy export (kWh)	305	274 (−10.2%)	305	240 (−21.3%)
Marina's energy cost (EUR)	760	756 (−0.5%)	791	783 (−1.0%)
Rental company's cost (EUR)	28.6	13.8 (−51.7%)	60.5	29.5 (−51.2%)
Self-consumption (%)	93.3	94.0 (+0.8%)	93.3	94.7 (+1.5%)
Self-sufficiency (%)	49.7	50.1 (+0.8%)	47.7	48.3 (+1.3%)

In the scenario with four EVs, the energy import was smaller compared to the case with eight cars—as the EV demand was approximately two-times lower. The V2G technology implementation resulted in a 0.6% and 1.2% decrease in this parameter, with respect to the scenarios with four and eight electric cars. Furthermore, the energy export reduced by 10.2% and 21.3%, which can be considered as a significant improvement of the marina's ICES operation. These enhancements led to, respectively, 0.5% and 1.0% cost savings for the marina, increasing self-consumption by 1.5% and self-sufficiency by 1.3%—for the future scenario.

Under the proposed pricing scheme for the rental company, its participation in the V2G initiative is remarkably beneficial, with weekly cost savings up to 51.7%. Taking into account the previously analysed positive V2G impact on the battery lifetime, the company presumably could be convinced to allow the bidirectional charging of their cars. The obtained results are very favourable, as the cooperation of flexible units and the smart marina's energy system is beneficial for all involved parties. This way, it is possible to obtain significant socio-economic advantages, benefiting all stakeholders. Fundamentally, the cost savings achieved by the marina can be distributed between the other smart grid participants—in this case, the rental company and sailors—encouraging flexible electricity consumption. A further increase in the number of electric cars is expected to additionally minimise the energy export to the public grid, leading to a better utilisation of the marina's renewable generation. In such a scenario, the relative benefits for the rental company are anticipated to remain at the same level, corresponding to approximately 50% cost savings—as a result of the participation in bidirectional power exchange.

Considering the apparent benefits from the V2G implementation, this technology could become a pivotal part of Ballen marina's future energy system. As discussed in Section 2, the V2G application should be taken into consideration only as the future scenario—since bidirectional charging standards are still under development. Nonetheless, the advantages of the V2G implementation are substantial, and the marina could techno-economically benefit in the future from the application of boat flexibility and EV bidirectional charging, enabling the integration of more renewable energy without additional grid reinvestment. The obtained results clearly show the improvements in the operation of Ballen marina's energy system, compared to the previous research in this area [28–30,45].

6. Conclusions

Ballen marina's electric cars can become an integral part of the community energy system, utilising their synergies with the local PV generation, BESS, and boat flexibility. The weekly EV usage profile was generated, utilising a stochastic approach to resemble daily variations in the driving pattern. The developed optimal management strategy proved the possibility to decrease the energy cost for the rental company, charging the cars during low-price periods. Furthermore, the integration of boat flexibility and smart EV charging resulted in the substantially enhanced energy system operation of the marina—with an improved load factor and reduced energy cost for all involved parties. In the future, the increased PV generation of the harbour may be utilised more efficiently with the implementation of the V2G technology. The benefits of bidirectional power flow for scenarios with four and eight electric cars are considerable, with ample advantages for the marina and the rental company. The greater integration of the analysed flexible units of the marina—boats and electric cars—results in significantly improved grid operation from both the technical and economic perspectives. Therefore, increasing the integration level is recommended to be taken into consideration in the upcoming years not only for the ICES of Ballen marina, but also for other community energy systems. The future works will be focused on evaluating the flexibility potential of the other loads of the marina, such as heat pumps, water pumps, washing machines, and the sauna.

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery energy storage system
BEV	Battery electric vehicle
CCS	Combined Charging System
DR	Demand–response

ESS	Energy storage system
EV	Electric vehicle
ICES	Integrated community energy system
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
SOC	State of charge
V2G	Vehicle-to-grid

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