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Smart Island Energy Systems: Case Study of Ballen Marina on Samsø

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***Abstract*—Integrated community energy systems are an emerging concept for increasing the self-sufficiency and efficiency of local multi-energy systems. This idea can be conceptualised for the smart island energy systems due to their geographical and socioeconomic context, providing several benefits through this transformation. In this study, the energy system of the Ballen marina—located on the medium-sized Danish island of Samsø—is investigated. Particular consideration is given to the integration of PV, BESS, and—in the future—flexible loads. For this purpose, the BESS is modelled, incorporating the battery degradation process. The possibilities to improve energy utilisation and maximise self-consumption from the marina's PV units are identified and evaluated, demonstrating a substantial enhancement of the local system operation.**

***Index Terms*—integrated community energy systems, smart island energy systems, multi-energy systems, battery energy storage system**

Nomenclature

$\delta_i^{\mathrm{b}+}/\delta_i^{\mathrm{b}-}$	Battery charging/discharging binary decision variable
$\delta_i^{\mathrm{g}+}/\delta_i^{\mathrm{g}-}$	Power import/export binary decision variable
$\eta^{\mathrm{b}+}/\eta^{\mathrm{b}-}$	Battery charging/discharging efficiency (%)
η^{b}	Battery round-trip efficiency (%)
τ	Time step size (h)
$\xi^{\mathrm{bf,\,cal}}$	Battery calendar ageing (%)
$\xi^{\mathrm{bf,\,cyc}}$	Battery cycle ageing (%)
ξ^{bf}	Total battery capacity degradation (%)
i	Index of time slot
k	Number of battery cycles
n	Number of time slots
t	Time (h)
C	Total energy cost for marina (€)
C^{+}/C^{-}	Energy buying/selling price (€/kWh)
$E_i^{\mathrm{b\,max}}$	Battery capacity (kWh)
$E_i^{\mathrm{b+max}}/E_i^{\mathrm{b-max}}$	Battery maximum charging/discharging rate (kWh)
$P^{\mathrm{b\,max}}$	Battery maximum power (kW)
$P_i^{\mathrm{b}+}/P_i^{\mathrm{b}-}$	Battery charging/discharging power (kW)
P_i^{b}	Battery power (kW)
$P^{\mathrm{g+max}}/P^{\mathrm{g-max}}$	Maximum power import/export (kW)
$P_i^{\mathrm{g}+}/P_i^{\mathrm{g}-}$	Power import/export (kW)
P_i^{g}	Power exchange with the grid (kW)
P_i^{l}	Electrical load (kW)
P_i^{pv}	PV production (kW)
DOD	Battery depth of discharge (%)
SC	Self-consumption (%)
$SOC^{\max}/SOC^{\min}$	Battery maximum/minimum state of charge (%)
SOC^{mean}	Mean battery state of charge during cycle (%)
SOC_i	Battery state of charge (%)
SS	Self-sufficiency (%)

I. Introduction

A. Motivation and Background

The ambitious goal of building a fossil fuel independent society by 2050 is a crucial objective to ensure the green future of Denmark [1]. The large-scale implementation of renewable energy sources (RES) is an essential approach to significantly decrease CO_2 emissions, mitigate climate change, phase out fossil fuels and provide sustainable development of the country [2]. Despite the undeniable ecological benefits, the intermittency of renewable energy is a fundamental challenge. The green generation is inherently dependent on atmospheric conditions, which are often changing rapidly and unpredictably. Consequently, several impediments can be identified, such as power fluctuations and storage necessity [3]. Therefore, proper integration of RES is a crucial element to assure the reliability of energy supply and high efficiency of the power system [4].

Implementation of alternative energy supply solutions also requires the broad involvement of consumers. Hence, the smart multi-carrier energy system solutions are primarily investigated in terms of local communities, resulting in integrated community energy systems (ICESs) [5]. The concept of ICESs involves a local-scale energy systems reorganisation, which enables the efficient integration of distributed energy resources (DER), engagement of local consumers, and far-reaching energy interconnection. Furthermore, the distributed generation can be optimally utilised, matching it with the local load via storage and demand response (DR) techniques [6].

B. Relevant Literature

Multi-carrier energy systems—integrating DER and flexible loads—benefit from real-time optimisation, ensuring efficient energy management. For this purpose, diverse optimisation techniques are adapted, minimising or maximising objective functions while satisfying specified constraints. Commonly, multi-energy optimisation aims to maximise grid self-sufficiency or minimise energy cost [7]. In [8], a decision tree algorithm has been utilised for peak-load reduction. Subsequently, in [9] fractional programming has been implemented for the cost efficiency optimisation. The dynamic programming has been used in [10] for the minimisation of electricity cost. A popular optimisation approach in multi-energy systems is mixed-integer linear programming, which has been adapted in [6], [7], [11]. Furthermore, evolutionary algorithms—such as genetic algorithm [12] or particle swarm optimisation [13]—have been previously utilised for solving both single-objective and multi-objective problems.

C. Contributions and Organisation

This paper proposes the optimal scheduling of the battery energy storage system (BESS) in the ICES of Ballen marina, located on the medium-sized Danish island of Samsø. The objective of the developed BESS strategy is to increase the self-consumption from local PV production, as well as enhance the harbour's self-sufficiency level. Furthermore, the possibilities to improve energy utilisation are identified. The novelty of this work includes the development of an algorithm for the marina's energy management, implementation of the BESS degradation model, as well as comparison of the established optimal energy scheduling with the previous research on Ballen marina [7].

The remainder of this paper is organised as follows. Section II outlines the marina description, along with the key parameters of its integrated community energy system. Moreover, the modelling of BESS and energy exchange is performed. Subsequently, Section III provides the methods used for this study. The simulation results of three study cases are demonstrated and analysed in Section IV. Ultimately, the conclusions and future works are presented in Section V.

II. Marina Description

On Samsø, due to offshore and onshore wind farms along with PV generation and biomass heating, renewable energy production exceeds the island's electricity demand. With the increasing number of EVs and heat pumps—replacing conventional fossil fuel solutions—the high level of multi-carrier energy integration is desirable. The prominent smart energy demonstration programme on Samsø takes place in Ballen marina—the largest and most visited island's harbour. [14]

A. Marina Parameters

With approximately 8 500 guests per year, the marina's load is highly dependent on tourism. The harbour is connected to the island's grid on a 400 V voltage level. Furthermore, 60 kWp PV plant and BESS (Xolta BAT-79 lithium-ion battery with 49 kW converter and nominal capacity of 237 kWh) are installed on the marina site—which sizes have been chosen according to available space and project's budget [15]. The docking boats constitute the most substantial electrical load, considering 340 available sockets for boats. In addition, several other substantial loads are installed in the marina, including heat pumps, sauna, wastewater pumping station, and EV charging points. The marina's energy system diagram can be found in [7] and [14].

Currently, the energy is traded between the marina and utility grid at flat pricing rates. Due to the inherent taxes, the energy buying price (0.21 €/kWh) is seven times higher than the selling one (0.03 €/kWh). Therefore, it is economically justified to prioritise the self-consumption of locally generated energy. Thus, the installed BESS is utilised to minimise the marina's energy exchange with the public grid. [14], [15]

The analysis is conducted based on publicly available data from Samsø Energy Academy [15]. The measurements—collected in 2016 on a 15-minute basis—are averaged to hourly resolution, resulting in 8784 samples for the simulation year. The Ballen marina's load and PV production profiles are shown in Figure 1.

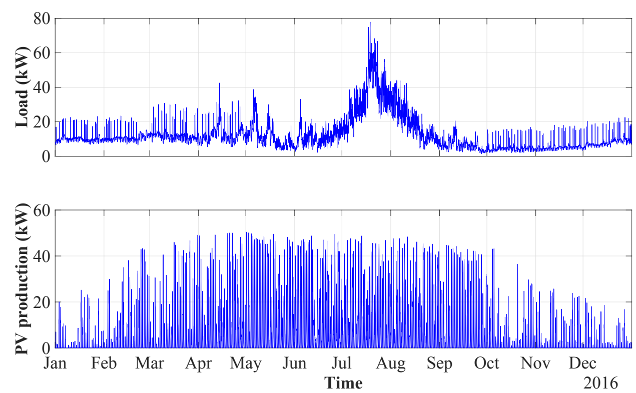

Fig. 1. Load and PV production profiles of Ballen marina

The total energy consumed during the simulation year is calculated as 104 744 kWh. The peak demand—related to the high tourist season—is visible in July, with the crest load reaching 77.8 kW. Moreover, electricity consumption is significantly lower in the autumn and winter months compared to the spring and summer periods. The annual marina's PV production is estimated as 55 625 kWh. The highest PV generation is observed in the spring and summer seasons, which is in line with the variability of the harbour's electricity demand. Nevertheless, the peak PV production (50.4 kW) is substantially lower than the peak demand—the remaining energy needs to be supplied from the external grid.

B. Modelling of BESS

The optimal utilisation of BESS requires adequate modelling and scheduling, which takes into account operation efficiency, energy and power constraints, as well as battery degradation over time. The BESS is modelled, considering the standard battery framework and dependencies, to be consequently used in mixed-integer linear programming optimisation [7].

Due to the conversion and storage losses—as well as an additional isolation transformer negatively impacting the efficiency—the BESS round-trip efficiency is equal to 82%. The charging and discharging efficiencies are assumed to be equal to the square root of the round-trip efficiency:

$$\eta^{\mathrm{b}+} = \eta^{\mathrm{b}-} = \sqrt{\eta^{\mathrm{b}}} \approx 90.6\% \tag{1}$$

The simulation is conducted to determine the optimal battery action for each time slot. Taking into account the resolution of available data, the length of each time slot is decided as $t = 1$ h. Thereby, the battery state of charge (SOC) at the end of each time slot is given by:

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

For each time slot, the maximum charging rate is bounded by the maximum state of charge, assumed as $SOC^{\max} = 97.5\%$, with regard to the battery capacity. This limitation, as well as the subsequent minimum SOC constraint, are introduced, as 5% of the battery capacity remains inaccessible—according to the BESS manufacturer. This way, the maximum charging rate is modelled as:

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

Similarly, the maximum discharging rate is limited by the minimum state of charge, assumed as $SOC^{\min} = 2.5\%$:

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

Obtaining the charging rates, the battery charging and discharging power must fulfil the following constraints:

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

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

The battery decision variables are introduced to prevent the simultaneous charging and discharging action of the BESS. Hence, the decision variables are restricted to be binary integers:

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

The simultaneous charging and discharging are avoided by permitting only one decision variable at each time slot to be active:

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

Furthermore, the charging and discharging power is constrained by the BESS converter capabilities, with the rated power of $P^{\mathrm{b\,max}} = 49$ kW:

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

Ultimately, the battery power is given by:

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

It is noted that the positive values of P_i^{b} indicate battery charging action, whereas negative ones point out the battery discharging process. The introduced model can be utilised to increase self-consumption from local PV production. In this manner, BESS action is dependent on the marina's load and PV generation at each time slot. For the forthcoming simulations, the initial SOC is assumed as $SOC_{i=0} = 50\%$. The flowchart of the desired battery operation is presented in Figure 2. Given the flowchart, the battery is anticipated to act as a buffer for excess PV generation.

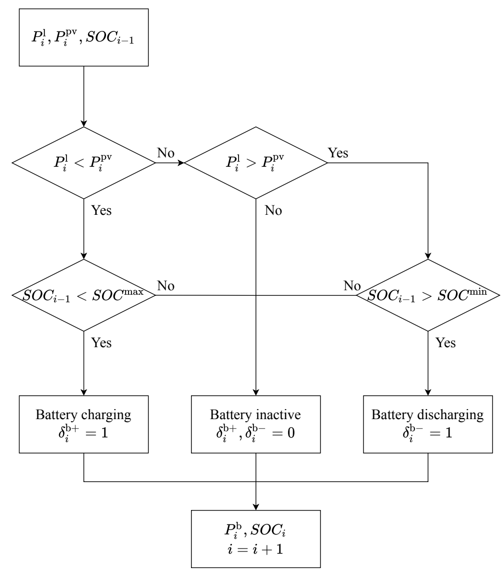

Fig. 2. Battery operation flowchart

The operation of Li-ion batteries is significantly affected by their degradation over time. The battery lifetime predominantly depends on idling and cycling operation, as well as operating temperature. Thus, calendar and cycle ageing modes can be distinguished, related to respectively idling at certain SOC level and charging/discharging cycles. [16]

The battery degradation is visible as a decrease in BESS maximum capacity and power capabilities. Nevertheless, the capacity fade is recognised as a more severe ageing mode, which also develops more rapidly. Therefore, calendar and cycle ageing—affecting solely battery maximum capacity—are considered in this model. The capacity fade equations are based on the laboratory-developed lifetime model of a standard Li-ion battery [17], with the operating temperature of 25°C.

The calendar capacity ageing—due to battery idling—can be estimated as:

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

Subsequently, the cycle capacity ageing depends on the depth of discharge, mean state of charge during cycle, and the number of cycles. Thereby, the capacity fade due to cycle ageing is given by:

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

Based on the battery SOC profile, a rainflow algorithm—named from a similarity of this method to the rain falling on a pagoda roof—is utilised to count cycles, as well as determine their corresponding DOD and SOC^{mean} [18]. Thereafter, the accumulated damage caused by different stress levels—for both calendar and cycle ageing—is calculated using Palmgren-Miner linear damage rule. As the battery end-of-life criterion, the capacity degradation of 20% is assumed [17]. Further, the total battery degradation is calculated as a sum of capacity fade caused by idling and cycle operation:

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

Finally, the maximum battery capacity is calculated at the end of each time slot, accounting for the capacity fade:

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

A healthy battery system is assumed for the initial conditions, with the maximum battery capacity equal to $E_{i=0}^{\mathrm{b\,max}} = 237\ \mathrm{kWh}$. The developed BESS model can be implemented as a part of an optimisation problem, with the aim to determine charging and discharging power for each simulation step.

C. Modelling of Energy Exchange

The energy exchange with the public grid is modelled for the implementation in the optimisation problem. The power import from the grid and power export are constrained by:

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

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

The maximum power import is equal to 86 kW, being limited by the fuse at the point of common coupling. On the other hand, the maximum power export equals 49 kW, due to the agreement with the utility grid. The grid decision variables are utilised to avoid the simultaneous energy import and export action. The decision variables are restricted to be binary integers:

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

In this manner, only one decision variable is permitted to be active at each time slot:

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

Subsequently, the energy exchange is given by:

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

The positive values of P_i^{g} signify energy import from the public grid, whereas negative ones indicate energy export. Finally, the power balance constraint—with marina's load, PV generation, battery action, and power exchange—needs to be satisfied:

$$P_i^{\mathrm{l}} + P_i^{\mathrm{b}} - P_i^{\mathrm{g}} - P_i^{\mathrm{pv}} = 0 \tag{20}$$

III. Optimal Operation of Integrated Community Energy System

The simulation of the ICES of the Ballen marina is conducted for the whole simulation year, with $n = 8784$ time slots. Three study cases are considered: without PV and BESS, without BESS, and finally—with PV and BESS

The performance of the harbour's energy system is assessed based on the energy cost, as well as self-consumption and self-sufficiency. The total energy cost is calculated as a difference between buying cost and selling revenue:

$$C = \sum_{i=1}^{n} \left(C^{+} P_i^{\mathrm{g+}} t - C^{-} P_i^{\mathrm{g-}} t\right) \tag{21}$$

Subsequently, the self-consumption of local PV generation is given by:

$$SC = \frac{\sum_{i=1}^{n} \left(P_i^{\mathrm{pv}} - P_i^{\mathrm{g-}}\right)}{\sum_{i=1}^{n} P_i^{\mathrm{pv}}} \tag{22}$$

Further, the self-sufficiency of the marina's energy system is calculated as:

$$SS = \frac{\sum_{i=1}^{n} \left(P_i^{\mathrm{l}} - P_i^{\mathrm{g+}}\right)}{\sum_{i=1}^{n} P_i^{\mathrm{l}}} \tag{23}$$

The scheduling of BESS is carried out as the optimisation process. The objective of the optimisation problem is to maximise the self-consumption of the marina's PV generation and thus minimise the power exchange with the public grid. With this objective function, the side product of optimal BESS scheduling is the minimisation of the marina's operation cost. The problem is solved in the MathWorks MATLAB R2020b environment, using mixed-integer linear programming. The optimisation is carried out for each time slot, resulting in the optimal operation of ICES with PV and BESS for the entire simulation year. The problem is formulated as:

$$\begin{aligned} \text{minimise} \quad & \sum_{i=1}^{n} \left(P_i^{\mathrm{g+}} + P_i^{\mathrm{g-}}\right) \\ \text{subject to:} \quad & (5)\text{–}(9), (15)\text{–}(18), (20) \end{aligned} \tag{24}$$

Constraints (5)–(9) are devised to limit the BESS action, accordingly to its parameters and SOC. Subsequently, constraints (15)–(18) are used to establish marina's energy exchange with the public grid. Moreover, constraint (20) is utilised to preserve power balance for each time slot. Ultimately, the simulation results are compared to identify the strengths and weaknesses of the marina's grid.

IV. Results and Discussion

A. *ICES Without PV and BESS*

The first scenario considers the marina site without any distributed generation and storage system. Within this framework, the entire load is supplied by the public grid. Since no PV generation is available in this scenario, self-consumption and self-sufficiency of the grid are not determined.

B. *ICES Without BESS*

The second simulation scenario considers the marina with an installed PV plant, nevertheless, the BESS is not implemented yet. The PV production is assumed to supply the local marina's demand in the first place, exporting the excess energy to the external grid. Furthermore, the missing energy—required to meet the entire demand—is imported from the grid. The energy exchange between the ICES and the public grid, for the simulation case without BESS, is presented in Figure 3.

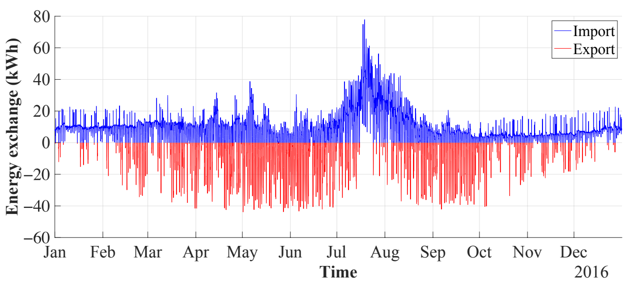

Fig. 3. Energy exchange of ICES without BESS

The highest energy import is observable in the summer months—when PV production is not sufficient to cover the load during peak tourist season. On the contrary, in the spring and early autumn months, a significant amount of energy is exported to the grid. Considering the divergence between buying and selling energy price, this phenomenon is unfavourable. Therefore, the subsequent scenario—with PV and BESS—is anticipated to improve the grid's behaviour.

C. *ICES With PV and BESS*

The final study case considers the ICES of Ballen marina with installed PV plant and BESS. The resulting battery power and SOC are presented in Figure 4.

It is observed that BESS is particularly active in the spring and early autumn months—when PV generation frequently exceeds the marina's demand. Nevertheless, the battery is idling at 2.5% SOC level for 4513 hours, which accounts for more than half of the simulation period. This phenomenon is especially visible in the winter months—when PV generation is low, as well as during summer—when demand is highest.

Furthermore, it is noticed that the battery power—both during charging and discharging action—is not reaching the converter capabilities. This is due to the fact that the power excess or deficiency is not high enough to achieve it for the entire length of any time slot. Nevertheless, in real life, there might be periods when the instantaneous power difference is higher than the hourly-averaged values.

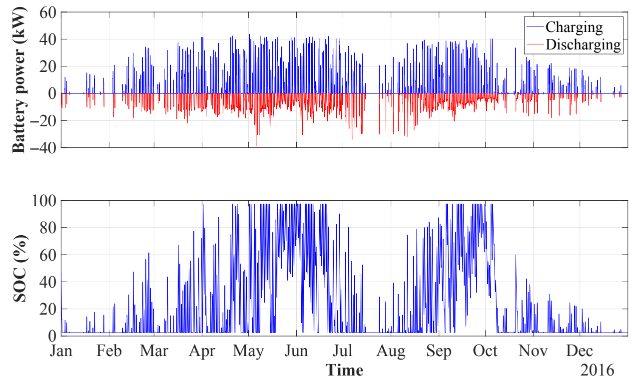

Fig. 4. Battery power and SOC for ICES with PV and BESS

The accumulated battery damage for the simulated year is equal to 3.08%. Considering the significant idling time, the damage caused by calendar ageing is dominant (1.81%), compared to the cycle ageing damage (1.28%). In this context, the expected BESS lifetime is estimated at 32.5 years. The obtained lifetime is more than double the expected lifetime (15 years), provided by the manufacturer [19]. This discrepancy can be explained by the significant idling time during the simulation period or tolerance for the battery's legal liability.

Consequently, the energy exchange of the ICES, with PV and BESS, is presented in Figure 5.

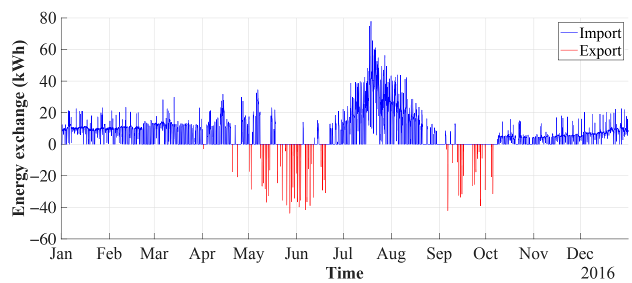

Fig. 5. Energy exchange of ICES with PV and BESS

It is noted that the energy export—with the help of BESS—has been completely eliminated in the winter months, and significantly reduced for other year seasons. The essential simulation results of the study cases are presented in Table I.

D. *Discussion*

Reflecting on the simulation results, the installation of a PV plant on the marina site resulted in a 26.3% decrease in energy import while reducing the total energy cost by 30.0%. Subsequently, the implementation of PV generation along with BESS resulted in improved outcomes—with a 45.5% and 45.9% decrease in energy import and cost, respectively. The significant effect of BESS installation is observed in energy export, decreasing this parameter by 86.9%. This is the equivalent of an increase in self-consumption by 89.6% and enhancement of self-sufficiency by 73.9%.

Implementing the optimiser, the resulting BESS operation coincides with the battery acting straight as a buffer. Moreover,

TABLE I
COMPARISON OF SIMULATION RESULTS FOR ICES OF BALLEN MARINA

Parameter	Case		
	No PV and BESS	No BESS	PV and BESS
Energy import (MWh)	105	77.4 (−26.3%)	57.2 (−45.5%)
Energy export (MWh)	–	28.3	3.71 (−86.9%)[1]
Buying cost (k€)	22.0	16.3	12.0
Selling revenue (k€)	–	0.848	0.111
Total cost (k€)	22.0	15.4 (−30.0%)	11.9 (−45.9%)
Self-consumption (%)	–	49.2	93.3 (+89.6%)[1]
Self-sufficiency (%)	–	26.1	45.4 (+73.9%)[1]

[1] Parameter change with respect to the scenario without BESS

the results are in line with the findings in [7]. The extended battery model has an insignificant influence on the overall simulation results since the battery degradation has a low impact on the battery operation during the first year of usage. Nevertheless, the negative effects of degradation will gain in importance over the longer term, impairing the benefits of BESS with each passing year. Furthermore, the obtained results prove that the battery is considerably underutilised—and additional calculations indicate that increasing PV plant capacity up to 120 kWp is economically viable.

The energy export could not be completely eliminated by the means of BESS, and therefore self-consumption of local PV generation can be further improved. Furthermore, the discrepancies between desired and experienced self-consumption would widen, considering the futuristic scenario with increased PV capacity. In this manner, the implementation of DR techniques is considered to additionally elevate the marina's energy system efficiency, ensuring the high integration and sustainability level of the ICES. For that reason, the application of DR techniques should be examined in future research. In addition to the possible increase in grid self-sufficiency, the introduction of flexible loads could also decrease the energy cost, considering the anticipated implementation of dynamic tariffs in the Ballen marina.

V. CONCLUSIONS

The energy system of the Ballen marina is a distinctive example of ICES, with high load dependence on tourism, as well as significant possibilities for further grid smartening. This paper proposes the optimal BESS scheduling strategy with the objective of increasing the marina's self-consumption of local PV generation. Considering the effect of PV and BESS installations, the conducted simulations prove a substantial enhancement of the harbour's system operation, with increased self-consumption, self-sufficiency, and reduced energy cost. The results of this study can be used in the context of other communities and regions, aiming to improve the exploitation of local RES production. Nevertheless, the flexibility of EVs and thermal loads is not utilised, leaving room for further improvements. The future works will be focused on harnessing flexibility from the controllable loads and evaluation of the possible benefits from the implementation of vehicle-to-grid (V2G) technology. In addition, load and generation forecasting uncertainty could be also taken into consideration in the future.

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