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EXECUTIVE SUMMARY OF THE THESIS

Techno-economic assessment and optimization of full-electric passenger vessels: the lake Iseo case study

TESI MAGISTRALE IN MOBILITY ENGINEERING

AUTHOR: MATTEO BELOTTI

ADVISOR: PROF. GIULIO GUANDALINI

CO-ADVISOR: ING. EMILIANO ZAMPOLERI, DOTT. DANIELE BRENNO FAUSTI

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1. Introduction

One-quarter of total greenhouse gas (GHG) emissions in the European Union are due to the transport sector [1]. The effort in reducing those emissions invests, in particular, the maritime sector. In 2023 the International Maritime Organization (IMO) set the objective of reducing carbon emissions by 20% for 2030 [2], in parallel the EU is striving for an 80% reduction by 2050 [3]. In this context, vessel electrification is emerging as one of the main solutions to reduce environmental impacts. On Lake Iseo, located in northern Italy, were recently introduced 2 new electric catamarans for passenger service. This would inevitably lead to an optimal test environment for analysing performances and energy consumption profiles of electric vessels on real operations. Moreover, since the shipyard is equipped with a $150kW_P$ photovoltaic (PV) plant and a $150kWh_{nom}$ stationary Li-Ion battery (BESS), this work will also focus on energy flows optimization by assessing the current energy management system strategy. In particular, it evaluates the impact on total costs not only by the introduction of a smart charging strategy, but also the possible BESS and PV capacity improvements.

2. New full-electric vessels

The two new catamarans were designed and manufactured by *AmpereShip*. The catamarans dimensions are: 26.32m length and 6.60m breadth with a maximum capacity of 140 passengers.

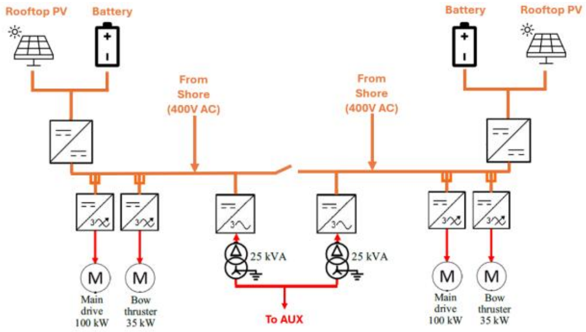

Figure 2.1: Catamaran's electrical scheme

Both ferries have the same electric propulsion architecture, this is composed of two sets of subsystems, one in each hull of the vessel. The main electric components architecture is described in Figure 2.1. A 750kWh Li-ion battery supply energy to the auxiliaries and the propulsion system (two 100kW electrical motors).

2.1. Data collection and analysis

An experimental campaign was conducted to evaluate vessels' real energy consumptions on real service operations. The testing period began in April with trials on service *L*, then continued with runs on service *IS1*, *C2* and *P1*. The key parameters collected during operation were the real-time State of Charge (SoC) of the batteries and the vessel's speed. Total energy consumption, average energy consumption rate and average navigational speed were calculated for each service (see Table 2.1).
The experimental campaign results highlight the coherent trend between average consumption rate and average navigation speed, as they align very closely to the manufacturer's motor power curve (see Figure 2.2). The comparison confirms both the tests accuracy and manufacturers' energy consumption forecast, even under real operating conditions.

Service	**Total energy [kWh_e]**	**Average consumption rate [kWh_e/h]**	**Average speed [km/h]**
L	491	131	17.5
IS1	392	113.7	16.5
C2	444	69.1	14.3
P1	357	54.5	12

Table 2.1: Test campaign results

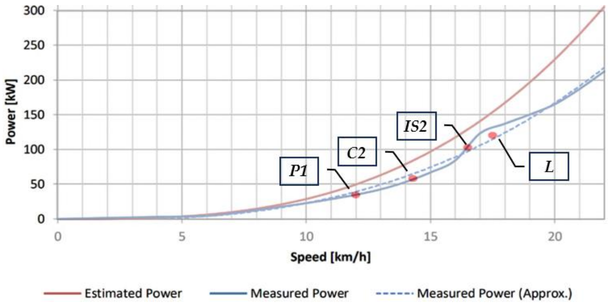

Figure 2.2: Motor power characteristic curve

The analysis is completed by considering stand-by consumption (i.e. when the vessels are docked) and the recharging phase. The average stand-by auxiliaries' power results to be equal to 5kW, while charging efficiency derived from daily data about the energy provided to the catamarans through the shore connection and the catamaran' energy consumption, is equal to 95%. The stand-by consumption and the charging efficiency have a crucial impact on the overall energy daily consumption. For example, the stand-by consumption is 1.2 times the energy consumption needed to perform service *L*.

2.2. Diesel vessels comparison

The electric catamarans' consumption is then compared to the diesel vessels' one on the tested duties. On the overall, the catamaran demonstrates lower energy consumption rate, confirming that the catamarans' propulsion system is more efficient, with increasing advantages for low navigational speeds (see Table 2.2).

Service	**ICE Vessel [kWh_{LHV}]**	**Electric Catamaran [kWh_e]**	**Average speed [km/h]**
L	577	491	17.5
IS1	1000	780	16.5
P1	554	356	12

Table 2.2: Vessels' energy consumption comparison

3. Energy flow optimization model

The main objective of this work is to carry out a detailed analysis of the energy flows in the shipyard, with only one catamaran covering the service *L*. This duty is of particular interest because it connects Pisogne and Lovere and, when the vessel is out of service, it is moored in the aforementioned shipyard. To perform this analysis, an optimization model is developed from a previous work on the recharge optimization for the E-bus fleet in Milan [4]. Firstly, it is assessed the control logic currently implemented to manage the energy flows within the shipyard PV+BESS plant. Then, the introduction of a "smart charging" strategy is simulated with a focus on the achievable cost reduction.

3.1. System architecture

The shipyard electrical plant has been modelled as displayed in Figure 3.1, with only 2 components providing input energy into the system: the grid connection and the rooftop PV plant. Whenever power generated by the PVs is in excess it can be redirected to the grid, or to the stationary BESS. The load of the system is made up of 2 main components: the facility loads and the energy to recharge the electric catamarans.

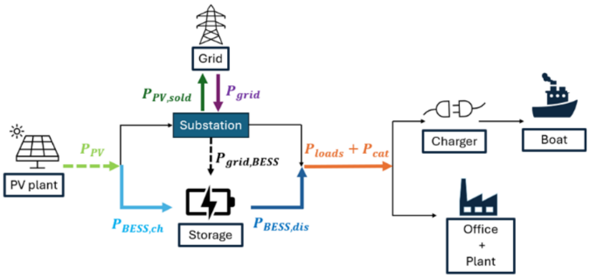

Figure 3.1: System architecture

3.2. Model description

The optimization model is developed as a MILP (Mixed Integer Linear Programming) algorithm. This kind of problems take different parameters as input and works with both integer and real variables. The variables submit to multiple linear constraints and the model solution is based on the minimization of the cost-objective function xx. The optimisation model is formulated using 2 sets relative to time dimensions: t set of the different time steps (e.g. with a timestep definition of 5 min) and m set of the different months.

Decision variables and Input parameters

Variables	Symbol	UoM
Energy purchased from the grid	$P^{t,m}_{grid}$	kWh
Energy from BESS to loads	$P^{t,m}_{BESS,dis}$	kWh
Energy from PV sold to the grid	$P^{t,m}_{PV,sold}$	kWh
Energy to charge the BESS	$P^{t,m}_{BESS,ch}$	kWh
Energy to discharge the BESS	$P^{t,m}_{BESS,dis}$	kWh
Energy to charge the catamaran	$P^{t,m}_{cat}$	kWh
Energy from grid to BESS	$P^{t,m}_{grid,BESS}$	kWh
State of catamaran (1 if recharging)	$s^{t,m}$	0/1
Catamaran's on-board battery SoC	$C^{t,m}_{cat}$	kWh

Table 3.1: Decision variables

Parameters related to the shipyard energy flows:

- $P^{t,m}_{PV}$: Power from the PV plant in the shipyard.
- $P^{t,m}_{loads}$: Power absorbed by shipyard facilities.

Quantities related to the stationary BESS:

- $\mathcal{B}$: it is the maximum achievable charging power increase per timestep.
- $P_{set,BESS}$: Normalised power profile to simulate reduced c-rate when SoC is above 85% during recharge or below 20% when discharged.
- $C_{BESS,max}$: BESS maximum capacity (150kWh).

Quantities related to the catamaran:

- $a^{t,m}$: Catamaran service schedule (1 if it is moored, 0 if on duty)
- c^{t}: Average consumption rate, which is assumed constant during the services.
- $C_{cat,max}$: Maximum catamarans' battery capacity, equal to 750kWh$_{\text{nom}}$.
- $P_{set,cat}$: Normalised power profile to simulate reduced c-rate when SoC is above 95% during recharge

Constraint equations

Here a summary of the main constraints implemented in the optimisation model:

1. Power balance

$$P^{t,m}_{grid} + P^{t,m}_{PV} + P^{t,m}_{BESS,dis} = P^{t,m}_{loads} + P^{t,m}_{PV,sold} + P^{t,m}_{BESS,ch} \tag{3.1}$$

The model needs to satisfy the power balance of the system. As visible in Equation (3.1), at each time step, the sum of all power generated is equal to the sum of all power consumed.

2. Catamaran state variable

$$s^{t,m} \leq a^{t,m} \tag{3.2}$$

Constraint (3.2) force the catamaran to be recharged only when it is moored in the shipyard.

3. Catamaran charging power constraint

$$P^{t,m}_{cat} = P_{set,cat} \cdot P_{max,cat} \cdot s^{t,m} \tag{3.3}$$

Constraint (3.3) limits the maximum recharging power using $P_{set,cat}$ and the maximum recharge power of the catamaran ($P_{max,cat}$). Lastly, $s^{t,m}$ ensures that recharging occurs only when moored.

4. Catamaran's battery capacity balance

$$C^{t+1,m}_{cat} = C^{t,m}_{cat} + (P^{t,m}_{cat} \cdot \eta_{cat,ch} - c^{t}_{cat}) \cdot \Delta t \tag{3.4}$$

Constraint (3.4) ensures catamaran's SoC balance when it is charged ($P^{t,m}_{cat}\eta_{cat,ch}$) or discharged ($c^{t}_{cat}$).

5. BESS charging power constraint

$$P^{t+1,m}_{BESS,ch} = P^{t,m}_{BESS,ch} + \mathcal{B} \tag{3.5}$$

Constraint (3.5) imposes a limit on the charging power increase per timestep of the BESS.

6. BESS charge and discharge constraint

$$P^{t,m}_{BESS,ch} \cdot P^{t,m}_{BESS,dis} = 0 \tag{3.6}$$

Constraint (3.6) guarantees that the BESS is not recharged and discharged simultaneously.

7. BESS charge balance constraint

$$P_{BESS,ch}^{t,m} \leq \max\left[0, P_{PV}^{t,m} - P_{loads}^{t,m} - P_{cat}^{t,m}\right] + P_{grid,BESS}^{t,m} \tag{3.7}$$

Constraint (3.7) ensures that the BESS can be charged only if the PV power is higher than the total loads. Moreover, grid power ($P_{grid,BESS}^{t,m}$) could be used to sustain BESS's SoC.

Objective function

$$\mathcal{C}_{total} = \mathcal{C}_{grid} + \mathcal{P}_{PV,fict} + \mathcal{P}_{grid,fict} + \mathcal{P}_{BESS,fict} + \mathcal{P}_{cat,fict} - \mathcal{R}_{grid} \tag{3.8}$$

The objective function aims to minimize total costs ($\mathcal{C}_{total}$), which is visible in Equation (3.8). It is calculated as the sum of total electricity supply costs ($\mathcal{C}_{grid}$), fictious costs related to selling PV energy to the grid ($\mathcal{P}_{PV,fict}$), to charge the BESS with the grid ($\mathcal{P}_{grid,fict}$), to wait charging the BESS ($\mathcal{P}_{BESS,fict}$), and to wait recharging the catamaran ($\mathcal{P}_{cat,fict}$). Revenues for selling energy from PV to the grid ($\mathcal{R}_{grid}$) are accounted as negative costs.

3.3. Model validation

The model parameters and constraints were validated using two separate three-day periods. In both cases the energy flows simulated fit well the real case with all the power profile trends correctly replicated (see Figure 3.2). Moreover, BESS SoC time evolution data presents a maximum error lower than 10% (see Figure 3.3). Finally, total energy produced by PV and sold to the grid, as well as the one purchased from the grid are within 1% error margin.

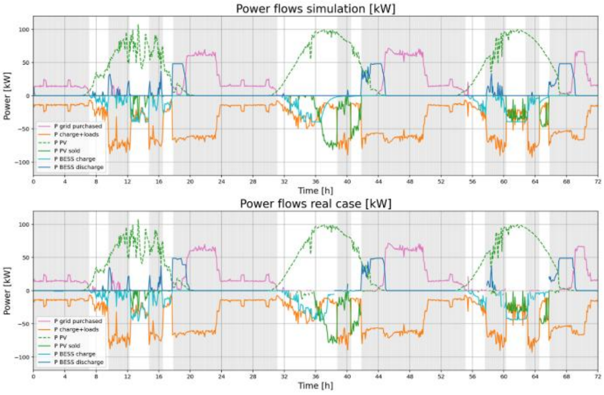

Figure 3.2: Power flows comparison between current case and the simulation (May 28-30)

It is worth noting that the control logic currently implemented does not account for electricity price variations and the catamaran is recharged as soon as possible and left connected to the chargers when not in use.

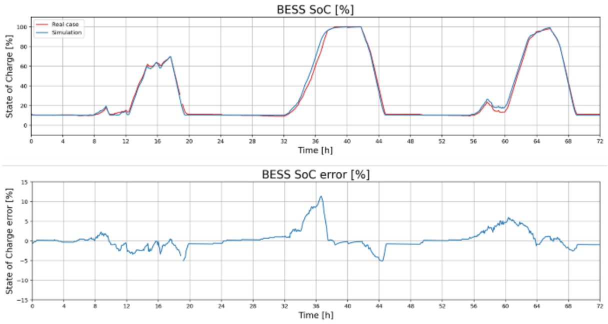

Figure 3.3: BESS SoC comparison between the current case and the simulation (May 28-30)

The model parameters and constraints were validated using two separate three-day periods. In both cases the energy flows simulated fit well the real case with all the power profile trends correctly replicated (see Figure 3.2). Moreover, BESS SoC time evolution data presents a maximum error lower than 10% (see Figure 3.3).

Finally, total energy produced by PV and sold to the grid, as well as the one purchased from the grid are within 1% error margin. It is worth noting that the control logic currently implemented does not account for electricity price variations and the catamaran is recharged as soon as possible and left connected to the chargers when not in use.

4. Smart charging results

The optimization model allows also to simulate the smart-charging feature dealing with variable energy price during the hours of the day. The comparison with the previous model's simulation is performed on a 3-day basis and on a year timeframe.

4.1. 3-day timeframe comparison

In the smart charging scenario, the energy is stored for a longer time since, during nighttime, the BESS is not used at all. In fact, night hours are the ones with cheaper energy prices, so BESS energy is preserved, and the model opt to buy from the grid. The energy stored is then used during period of high grid energy prices (see BESS SoC Figure 4.1). The optimal charging schedule avoids performing the charging during hours with higher electricity prices but opts to charge the catamaran anytime there is power coming from the PVs and during nighttime when the prices are lower (see the red line in Figure 4.1). As a result, PV energy self-consumption decreases, especially for charging the catamaran, since the objective of the model is costdriven. Another key advantage of using a smart charger, which is actually capable of modulating catamaran's recharging power, is its ability to bypass the BESS and transfer energy directly to the catamaran. By avoiding storage-related losses, the overall system efficiency is improved. The useful effect is that for both simulated periods the Cost of Energy (CoE) is 10% lower for the smart charging scenario.

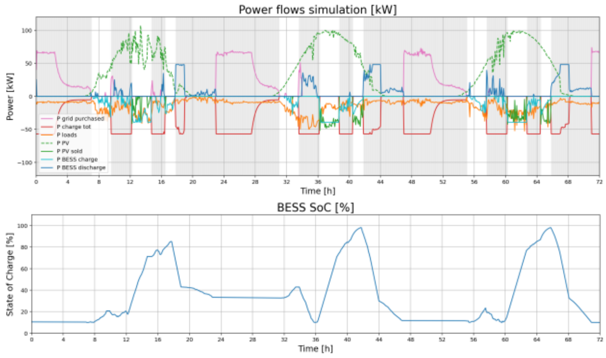

Figure 4.1: Power flows and BESS SoC simulated by the improved model (28-30 May)

4.2. Year comparison

A yearlong analysis of the system operations is then performed, adapting data from three reference months: February, March and June. Number of service day and total PV generation are scaled down to make each month coherent.

The smart-charging scenario reduces daily grid energy consumption by 4.5% compared to the current case, as PV energy exported to the grid drops by 10%. The optimized charging behaviour and improved BESS operation further lower CoE for the smart charging case of 10%. Overall, this translates into an annual cost reduction of approximately 6k€. Finally, due to the more efficient use of self-produced renewable energy, the average WtW emission intensity shows noticeable improvement with a reduction of 4.5%.

4.3. Monthly simulation

The validated version of the model (see section 3.2) is applied to simulate February, March and June operations. Among the three months, February exhibits the highest total energy consumption and the largest share of energy drawn from the grid, since the PV production is almost absent. As a result, the cost of operating service *L* with the battery-electric catamaran is slightly higher than with the diesel vessel: 160€/day and 155€/day, respectively. Despite that, operating the diesel vessel is still not the best solution, in fact the daily cost of keeping the catamaran docked should also be accounted (i.e. due to the auxiliaries' energy consumption which costs about 27€/day), which means that employing the catamaran is more convenient.

5. Design optimization

A modified version of the model is then developed to assess a potential addition of PV power capacity that can improve the economic performance. For this purpose, the objective function (see Equation (3.8)) is updated by adding the costs related to the new PV plant investment ($C_{PV,add}$), as visible in Equation (5.1).

$$C_{total}^{design} = C_{total} + C_{PV,add} \tag{5.1}$$

The model indicates that installing an additional PV capacity equal to 87kW led to an overall cost reduction of 1.1%.

To be more exhaustive, a multi-dimensional sensitivity analysis is then performed to evaluate how costs varying the PV installed capacity and BESS storage. The result shows that increasing BESS capacity is never economically convenient while a PV plant equipped with a capacity of 225kW$_{peak}$ provide the best performance. However, the LCOE reduction (-1.1%) is small and can hardly justify an investment, that anyway could improve energy independence and reduce impact of prices volatility. The analysis suggest that the existing shipyard infrastructure is already correctly sized.

6. Conclusions

This thesis analysed performances and energy consumption of a full-electric passenger catamaran operating on Lake Iseo, through an experimental data collection campaign. The measured consumptions on four different service routes align very closely to the manufacturer's power curve, confirming that the catamaran consumption matches the expected one, even under actual operating conditions. With a stand-by auxiliaries' consumption equal to 5kW, the charging efficiency was estimated at 95%. Because of these additional consumptions, it is more convenient to maximise the employment of the electric catamaran, even during month with small PV energy production, like February.

The optimization model was then improved to assess the current energy management system strategy and evaluate the reduction on electricity costs achievable by adopting a smart charging strategy. Simulation on 3-days and on a year timeframe demonstrated that cost reduction is around 10% (e.g. -6k€/y) for the smart charging scenario while also improving environmental performances (e.g. -2.2ton$_{CO2}$/y). Finally, an analysis of the existing infrastructure indicated that the current system is already well sized. Installing additional BESS storage is not convenient while extra PV capacity (up to 75kW$_P$) provides just marginal reduction in terms of cost of electricity supply (-1.1%). The model and analysis developed can be extended to evaluate catamaran operations on other routes, support the planning of new catamarans' services and to identify the optimal design of future electric vessel with the objective of a complete fleet electrification.

7. Bibliography

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8. Acknowledgements

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