PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

A MILP approach for hybrid energy systems design for sustainable maritime mobility

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Abstract:

In this paper, an optimization algorithm based on a Mixed-Integer Linear Programming (MILP) solver is developed to determine the best energy generation solutions for marine applications. Environmentally sustainable systems (e.g., fuel cells and batteries), heat recovery devices (e.g., HRSG and Organic Rankine Cycles) and traditional power technologies (e.g., diesel generators and fired boilers) are modelled as linear systems to simulate their off-design performance. The tool considers thermal, electrical and propulsion power demands, space constraints, fuel type and availability for up to three main-vertical zones of the ship. From this information, the optimizer identifies the energy system configuration which minimizes a cost optimization function. The objective function considers the actualized capital costs of each technology (based on real market data and updated literature review), fuel costs and CO_2 emissions taxes.
In this article, the case study of a cruise ship is considered. The optimization is performed referring to real historical load demands of the cruise ship and several typical mission profiles are considered to simulate a whole operational year.
Then, the same optimization is performed after a reduction of the price of H2, which is expected in the near future according to the latest market forecasts. Thanks to this analysis, it is possible to determine the influence of this economic parameter on the optimal on-board power generation configuration.
It is worth noting that the approach presented here has a general validity and can be applied for the optimization of various typologies of maritime vessels. Moreover, the MILP algorithm could be easily expanded to consider additional demands (e.g. cooling power), constraints (e.g., weight), and power systems.

Keywords:

MILP; Energy systems; optimization model; sustainability; alternative fuels.

1. Introduction

It is a matter of fact that, as total final energy consumption is increasing more and more at global level (298 EJ in 2000, 365 EJ in 2010 and 418 EJ in 2019), CO_2 emissions are growing as well (22.3 Gtons in 2000, 30.6 Gtons in 2010, 33.6 Gtons in 2019) [1]. Despite recent international energy policies that are trying to limit the increase, it is evident that further efforts must be done to comply with the 2015 Paris agreement (COP21). According to IEA data, electricity and heat production is the most impactful sector (14.0 Gtons), followed by transports (8.2 Gtons). The maritime sector represents an important contributor, responsible for the emissions of nearly 3% in terms of CO_2 (1 Gton/year). In order to decrease the impact of this sector, the International Maritime Organization (IMO) set a long-term strategy in 2018, with the ambitious goal of reducing transport-related CO_2 emissions of 40% by 2030, with the final target cut of 70% by 2050, compared to 2008 levels [2]. In 2023 the strategy is going to be revised, with the possibility of introducing further reduction targets. Furthermore, the European Commission has recently proposed adding maritime transport to the EU Emissions Trading System (EU-ETS) [3]. More in detail, The Commission is proposing to extend the scope of the EU-ETS to cover CO_2 emissions from all cargo vessels and passenger ships above 5000 gross tons, regardless of the flag they fly. The extension will include, starting from 2024: (i) all emissions from ships calling at an EU port for voyages within the EU; (ii) 50% of the emissions from voyages starting or ending outside of the EU; (iii) emissions that occur when ships are at berth in EU ports [3]. To reach the ambitious targets of emissions reduction, many parallel strategies can be adopted [4][5], including optimization in vessel design, speed reduction in navigation, use of alternative systems for power propulsion (i.e. fuel cells) and alternative fuels (i.e. biofuels, e-fuels) [6][7]. As far as power systems are concerned, the use of different kinds of fuel cells has been investigated in recent literature [8][9][10], focusing on: (i) high temperature Solid Oxide Fuel Cells

https://doi.org/10.52202/069564-0131

(SOFC), usually in hybrid systems configuration to increase efficiency [11] (up to 60%); (ii) low temperature Proton Exchange Membrane Fuel Cells (PEMFC), directly fuelled by hydrogen, which represent a zero emissions solution. The latter solution is the most employed today, in particular in research vessels as reported in recent literature. Regarding fuels, many alternatives are possible to replace Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), which are the most employed today and have high CO_2 emissions (about 3.1 $kgCO_2$/kg fuel). Natural gas is an alternative [12], however larger volumes are required for storage on-board and it only allows for a limited reduction (specific emission 2.75 $kgCO_2$/kg fuel). The use of hydrogen [13], ammonia [14], or other low carbon fuels is under investigation for several types of vessel [15].

To compare the different possible solutions in terms of power propulsion and storage technologies, it is important to develop reliable tools and models able to identify the best alternatives [16][17][18], taking into proper account the constraints of the problem, such as the volume and weight constraints of the vessel, the navigation route and the required performance in terms of autonomy and maximum power. The use of Mixed-Integer Linear Programming (MILP) models is largely recognized to optimize the distributed energy systems [19], also in presence of energy storage systems and not programmable renewable energy sources [20]. However, only a few applications of MILP models for power propulsion and fuel storage on-board maritime vessels are available in literature [21]. MILP models have never been developed before to investigate a wide spectrum of innovative technologies for a maritime application considering a time-dependent simulation on one year. In this paper, the tool developed by the Authors aims at: (i) choosing the optimal installation mix to meet the energy demands of the ship (electrical and thermal), while considering the most relevant constraints; (ii) minimizing an objective function which represents the annual costs.

2. Model Description

This section describes the optimization model developed for this study. It was designed as a tool capable of supporting the preliminary design phase of the energy systems installed on a ship. The optimization is performed by comparing different technologies for the generation of onboard electric and thermal power. The ship layout is split into three Main-Vertical-Zones (MVZ): each main-vertical-zone respects the tool constrains in order to identify the optimum location for each technology. The optimization model was tested considering a cost-based optimization function, which includes taxes on CO_2 emissions.

2.1. Library and user-interface

The optimization model was developed in MATLAB, while the optimization procedure relies on the BNB built-in solver of the Yalmip toolbox [19]. Within Yalmip, the GUROBI optimizer was adopted. This optimizer implements a standard branch & bound algorithm [20] to solve different kinds of mixed-integer problems [20][21]. The following technologies have been considered for electrical and thermal energy production:

- Internal Combustion Engines: Diesel Generators (DG).
- Heat Recovery System Generators (HRSG).
- Organic Rankine Cycles (ORC).
- Fire Boilers (FB).
- Heat Pump (HP)
- Battery Electrical Storage (BES).
- Proton-Exchange Membrane Fuel Cells (PEMFC).

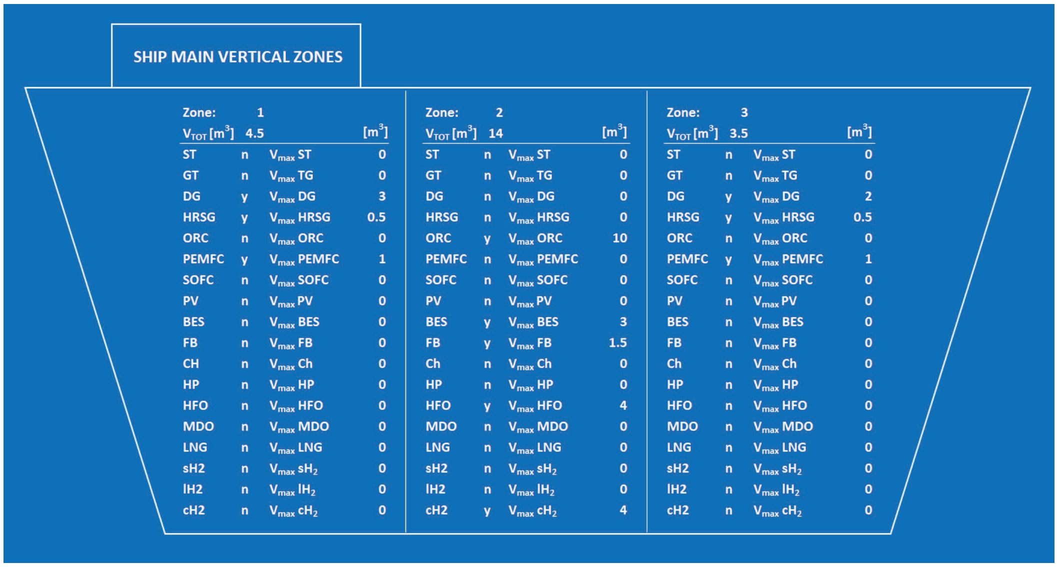
Each technology requires a certain amount of primary energy source. Heat recovery systems (HRSG, ORC) or storages (BES) interact with the ship balance depending on their efficiency and usage. Then, Diesel Generators, Fired Boilers and PEMFCs require a primary energy source. The fuel of these technologies is considered by the tool as a limited energy source: if the fuel tank is empty, the associated technology is shut down. The type of fuel and storage systems implemented are:

- Tank for liquid storage: HFO, MDO, LNG, liquid hydrogen.
- Tank for gas storage: compressed hydrogen.
- Metal Hydrides (MH) for solid hydrogen storage.

Some system contributes to the production of both thermal and electrical power, which are requested to satisfy the demands of the ship. Assuming that a propulsion unit driven by an electric generator is installed on the ship, the propulsive power is included in the electricity balance. The propulsive demand is increased to consider an overall efficiency for energy transformation of 95%.

The user interfaces with an Excel worksheet (Figure 1) to specify which technologies will be considered in the simulation, the volumes allocated to each technology and their distribution in each main vertical zone.

https://doi.org/10.52202/069564-0131



Zone: 1				Zone: 2				Zone: 3			
V_{TOT} [m^3] 4.5			[m^3]	V_{TOT} [m^3] 14			[m^3]	V_{TOT} [m^3] 3.5			[m^3]
ST	n	V_{max} ST	0	ST	n	V_{max} ST	0	ST	n	V_{max} ST	0
GT	n	V_{max} TG	0	GT	n	V_{max} TG	0	GT	n	V_{max} TG	0
DG	y	V_{max} DG	3	DG	n	V_{max} DG	0	DG	y	V_{max} DG	2
HRSG	y	V_{max} HRSG	0.5	HRSG	n	V_{max} HRSG	0	HRSG	y	V_{max} HRSG	0.5
ORC	n	V_{max} ORC	0	ORC	y	V_{max} ORC	10	ORC	n	V_{max} ORC	0
PEMFC	y	V_{max} PEMFC	1	PEMFC	n	V_{max} PEMFC	0	PEMFC	y	V_{max} PEMFC	1
SOFC	n	V_{max} SOFC	0	SOFC	n	V_{max} SOFC	0	SOFC	n	V_{max} SOFC	0
PV	n	V_{max} PV	0	PV	n	V_{max} PV	0	PV	n	V_{max} PV	0
BES	n	V_{max} BES	0	BES	y	V_{max} BES	3	BES	n	V_{max} BES	0
FB	n	V_{max} FB	0	FB	y	V_{max} FB	1.5	FB	n	V_{max} FB	0
CH	n	V_{max} Ch	0	Ch	n	V_{max} Ch	0	Ch	n	V_{max} Ch	0
HP	n	V_{max} HP	0	HP	n	V_{max} HP	0	HP	n	V_{max} HP	0
HFO	n	V_{max} HFO	0	HFO	y	V_{max} HFO	4	HFO	n	V_{max} HFO	0
MDO	n	V_{max} MDO	0	MDO	n	V_{max} MDO	0	MDO	n	V_{max} MDO	0
LNG	n	V_{max} LNG	0	LNG	n	V_{max} LNG	0	LNG	n	V_{max} LNG	0
sH2	n	V_{max} sH$_2$	0	sH2	n	V_{max} sH$_2$	0	sH2	n	V_{max} sH$_2$	0
lH2	n	V_{max} lH$_2$	0	lH2	n	V_{max} lH$_2$	0	lH2	n	V_{max} lH$_2$	0
cH2	n	V_{max} cH$_2$	0	cH2	y	V_{max} cH$_2$	4	cH2	n	V_{max} cH$_2$	0

Figure 1 – The Excel user interface where the inputs of the MILP model can be defined.

Then, the user selects from a database the models to be compared during the simulation for each technology. The database contains the information required for optimisation computation and performance estimation of energy systems. **Appendix A** lists the data stored in the database. The model determines certain technical working characteristics of the systems under investigation based on their performance and thermal/electricity demands.

2.2. Constraints

The solution found by the MILP model is limited by four different types of constraints that are implemented on the algorithm:

- Operative constraints.
- Size constraints.
- Specific constraints of each energy system.
- Balance constraints: they allow the balance constraints of electrical and thermal demand and ensure continuity in the energy flow where energy systems interact (i.e. DG, HRSG ORC). They also verify the overall plant volume against the available space.

Operative constrains are necessary to guarantee that every variable under consideration have physical limits. Usually, all the technology considered in this tool have a minimum power output and a maximum power output. Size constraints ensure that each energy system respects an overall volume constraint. For each main vertical zone, the user defines both the volume dedicated to each specific technology and the total volume available in that main-vertical-zone. So, over imposing a total main-vertical-zone constraint is possible to guarantee that all the technologies installed don't exceed the volume available.
Every energy system must respect the constraints characteristic of the physics representing it, which correlate power (thermal and electrical), efficiency, current, consumption, etc (Table 1). In order to maintain the problem linear, the tool considers a linear correlation to evaluate the technologies off-design, as presented in the following table. Also, binary variables are limited to guarantee that a technology installed can be set on or off by the tool just in case it is installed.

Table 1 – System constrains description.

	System constraints
DG $\nabla d = 1 \dots N^{DG}_{model}$; $\nabla g = 1 \dots N^{DG}_{max}$	$x^{DG} \leq y^{DG}$ $\eta^{DG} = \alpha\, P^{DG}_{el} + \beta\, x^{DG}$; $P^{DG}_{th,diss} = P^{DG}_{el}(1-\eta^{DG})$; $\dot{m}^{DG}_{fuel} = \dfrac{P^{DG}_{el}}{\eta^{DG} LHV_{fuel}}$
HRSG $\nabla h = 1 \dots N^{HRSG}_{model}$; $\nabla r = 1 \dots N^{HRSG}_{max}$	$x^{HRSG} \leq y^{HRSG}$ $\eta^{HRSG} = \alpha\, P^{HRSG}_{th,out} + \beta\, x^{HRSG}$; $P^{HRSG}_{th,in} = \dfrac{P^{HRSG}_{th,out}}{\eta^{HRSG}}$

ORC $\nabla o = 1 \dots N_{model}^{ORC}$; $\nabla c = 1 \dots N_{max}^{ORC}$	$x^{ORC} \leq y^{ORC}$ $\eta^{ORC} = \alpha\, P_{el}^{ORC} + \beta\, x^{ORC}$; $P_{th,in}^{ORC} = \frac{P_{el}^{ORC}}{\eta^{ORC}}$
FB $\nabla f = 1 \dots N_{model}^{FB}$; $\nabla b = 1 \dots N_{max}^{FB}$	$x^{FB} \leq y^{FB}$ $\eta^{FB} = \alpha\, P_{th}^{FB} + \beta\, x^{FB}$; $\dot{m}_{fuel}^{FB} = \frac{P_{th}^{FB}}{\eta^{FB} LHV_{fuel}}$
HP $\nabla h = 1 \dots N_{model}^{HP}$; $\nabla p = 1 \dots N_{max}^{HP}$	$x_{cool}^{HP} + x_{heat}^{HP} \leq y^{FB}$ $COP^{HP} = \alpha\, P_{heat}^{HP} + \beta\, x_{heat}^{HP}$; $EER^{HP} = \alpha\, P_{cool}^{HP} + \beta\, x_{cool}^{HP}$ $P_{el,in}^{HP} = \left(\alpha\, P_{heat}^{HP} + \beta\, x_{heat}^{HP}\right) + \left(\alpha\, P_{cool}^{HP} + \beta\, x_{cool}^{HP}\right)$
PEMFC $\nabla p = 1 \dots N_{model}^{PEMFC}$ $\nabla e = 1 \dots N_{max}^{PEMFC}$	$x^{PEMFC} \leq y^{PEMFC}$ $\eta^{PEMFC} = \alpha\, P_{el}^{PEMFC} + \beta\, x^{PEMFC}$; $\dot{m}_{H_2}^{PEMFC} = \frac{P_{el}^{PEMFC}}{\eta^{PEMFC} LHV_{H_2}}$
BES $\nabla b = 1 \dots N_{model}^{BES}$ $\nabla s = 1 \dots N_{max}^{BES}$	$x_{ch}^{BES} + x_{disch}^{BES} \leq y^{BES}$ $C_{(t,w+1)}^{BES} = C_{(t,w)}^{BES} + \Delta t \left(P_{ch,(t,w)}^{BES} \eta_{ch}^{BES} - \frac{P_{disch,(t,w)}^{BES}}{\eta_{disch}^{BES}} \right)$; $C_{(t,1)}^{BES} = C_{max}^{BES}$ $\sum_w \left(P_{ch}^{BES} \eta_{ch}^{BES} - \frac{P_{disch}^{BES}}{\eta_{disch}^{BES}} \right) \geq 0$
FUELS	$SoC_{(t,w+1)} = SoC_{(t,w)} - \sum_{i=1}^{Numb.Techn.} \dot{m}_{fuel}^{i}$; $SoC_{(t,1)} = SoC_{max}$

2.2.1. Balance constraints

Balance constraints are presented in Table 2. These constraints have been introduced in order to guarantee the overall thermal and electrical energy balances of the ship. Also cooling demand has been introduced but it's not considered by the model at this stage.

Table 2 – Balance constraints description.

Balance Constraints
Electrical Balance $\sum_d \sum_g P_{el}^{DG} + \sum_o \sum_r P_{el}^{ORC} + \sum_f \sum_c P_{el}^{PEMFC} + \sum_b \sum_s P_{disch}^{BES} - D_{el} - \sum_h \sum_p P_{el,in}^{HP} - \sum_b \sum_s P_{ch}^{BES} = 0$
Thermal Balance $\sum_h \sum_r P_{th,out}^{HRSG} + \sum_f \sum_b P_{th}^{FB} + \sum_h \sum_p P_{heat}^{HP} - D_{th} = 0$ $\sum_d \sum_g P_{th}^{DG} - \sum_o \sum_r P_{th,in}^{ORC} = 0$

2.3. Optimization Function

The objective function adopted aims to minimise the costs of the ship considered. Furthermore, the tool includes fuel costs and CO_2 taxes. The main technologies costs considered by the objective function are:

- The total Installation Cost (1) obtained by the Capital Cost (CC) of each technology considered (s) and installed (i) adjusted by the Capital Recovery Factor (CRF).
- The total cost of the fuel consumed (2) during navigation into the time-lap considered (t) and every cruise profile (w). This equation takes into account the different costs for each fuel considered (f).
- Taxes due to CO_2 emissions (3).

$$Tot.Inst.Cost = \sum_s \sum_i CC_i\, CRF_i \quad where, \quad CRF = \frac{(1-r)^{UL}}{(1+r)^{UL} - 1} \tag{1}$$

$$Tot.FuelCost. = \sum_w \sum_t \sum_f \dot{m}_f\, \Delta t\, c_{fuel} \tag{2}$$

https://doi.org/10.52202/069564-0131

$$EmissionCost. = \sum_w \sum_t \dot{m}_{CO_2} \, \Delta t \, c_{tax} \quad (3)$$

The time lap adopted for simulation considers a whole cruise from port to port for one year. Costs are influenced by the number of cruise that the ship schedule during the year

3. Analysis and Results

3.1. Case study

To verify the correct operation of the MILP optimizer presented in Section 2, the case study of a passenger ferry boat was considered. The specifications of the boat, as well as its daily path and load profile were derived from the study by Rafiei et al. [22][5]. The ferry boat has an overall length of 47 m and in this specific scenario it sails with an average speed of 11 knots and a maximum speed of 13 knots. To guarantee the correct operation of the ferry boat, a propulsion system with at least 600 kW nominal power must be installed onboard. Moreover, the electrical power required by the auxiliary systems must be taken into account, both during navigation and while docked in port.

The ferry boat is used to carry passengers across a bay, following the same navigation plan every day:

- 06.00: departure from the port A
- 10.00: arrival at port B
- 13.00: departure from the port B
- 18.00: arrival at port C
- 20.00: departure from the port C
- 01.00: arrival at port A

Figure 2 shows the propulsion and auxiliary power demands for each hour of the navigation plan, specifying if the ferry boat is sailing or is docked in that moment.

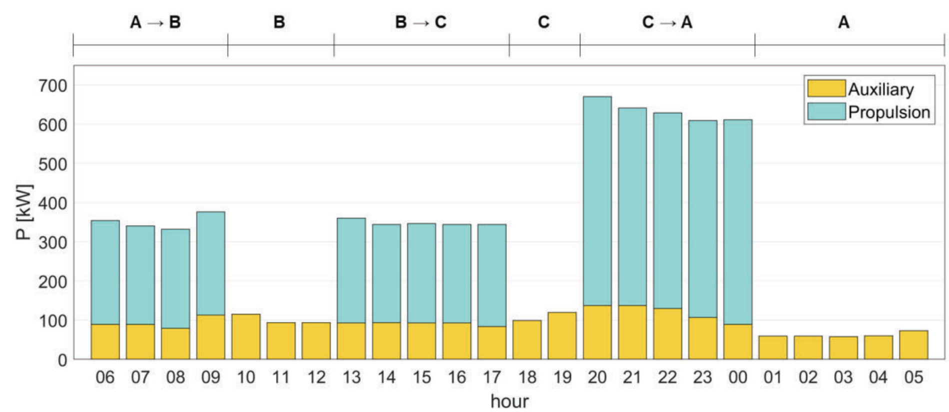


Figure 2 – Load profile of propulsive power and electrical power of the auxiliary systems; on the top it is specified if the ferry boat is sailing between ports or if it is docked.

For this analysis, only the port A is supposed to be equipped for cold ironing, and the BES are always completely charged at the beginning of each daily path (6.00).

The data used in [22] include only information of propulsive and auxiliary electrical loads. However, the MILP algorithm was designed to optimize the generation onboard of both electric and thermal power. Therefore, three possible daily weather conditions (i.e., hot, mild, cold) were defined, associating a different thermal load profile to each one of them:

- Hot weather: no thermal load – 92 days a year
- Mild weather: low thermal load – 151 days a year
- Cold weather: high thermal load – 122 days a year

Similarly to the electrical load of the auxiliary systems, the thermal load is present also when the ferry boat is docked. Figure 3 show the thermal load profiles for mild and cold weather, respectively.

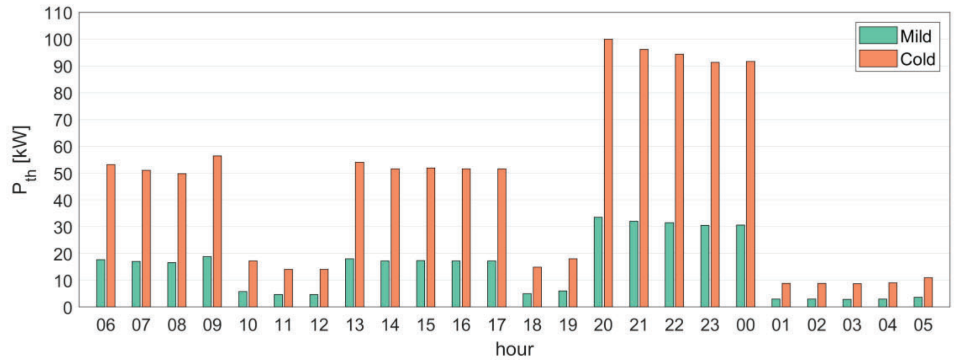


Figure 3 – Load profiles of thermal power for days with mild and cold weather.

3.2. Current scenario optimal solution

This section presents the results of a simulation using the current scenario: CO_2 tax 100€/ton, according to recent ETS [23] and hydrogen cost 6€/kg [24]. The technologies considered by the tool to minimise the objective function are listed in the Table 3, together with the best resulting configuration.

Table 3 – Optimization results, considering the actual scenario.

Supplier	Model	N° of elements installed	CAPEX / FuelCost [€/unit] / [€/y]
	Diesel Generator		
Solè Diesel	SDZ-205	1	35750
Solè Diesel	L1306C2 MSD	1	147500
Isotta Fraschini	SDZ-280	0	-
	Organic Rankine Cycle		
Orcan Energy	eP M 050.100 HP	0	-
Zuccato Energia	ZE-30-ULH	0	-
	Proton Exchange membrane Fuel Cell		
Genevos	HPM-15	0	-
Nuvera	E-45-HD	0	-
Nuvera	E-60-HD	0	-
	Battery Electrical Storage		
Corvus Energy	Orca Pack249	0	-
Nidec	Marine battery pack	3	48000
	Heat Recovery System Generators		
Siemens Energy	100	2	9900
Siemens Energy	10	1	990
	Fired Boiler		
AlphaLaval	Aalbotg CHB	0	-
AlphaLaval	Aalbotg CHB	1	4000
	Fuel Considered		
DG:	Heavy Fuel Oil		249150
FB:	Heavy Fuel Oil		
PEMFC:	Compressed green hydrogen		-
	Emissions		
CO_2			177190

The selection of these items is the outcome of some preliminary tests necessary to roughly identify the size of the systems which may potentially be installed. Therefore, some technologies have been excluded as too small or too large for this case study.

The results (Figure 4 and Figure 5) led to a configuration where the PEMFC technology is not present due to the high fuel cost. However, three battery modules were installed to manage the electrical load in combination with a smart modulation of the diesel engines. The capital cost of this technology is offset by the lower fuel consumption of the engines and the reduction in annual CO_2 emissions. The configuration also includes the installation of 3 HRSGs and 1 FB. It is clear that in the current scenario the most competitive technology is still the Diesel Generator due to its compactness, low cost per unit of power and low fuel cost.

The tool also determines the best strategy for using these technologies to cover the electricity and heat demands. It is important to observe that the electrical load distribution in the first two mission profiles (hot and

 https://doi.org/10.52202/069564-0131

mild weather) is similar, so it is presented only once in this article. On the other hand, in the third mission profile (cold weather), the electrical power generation strategy is notably influenced by the high thermal demand of the ferry boat.

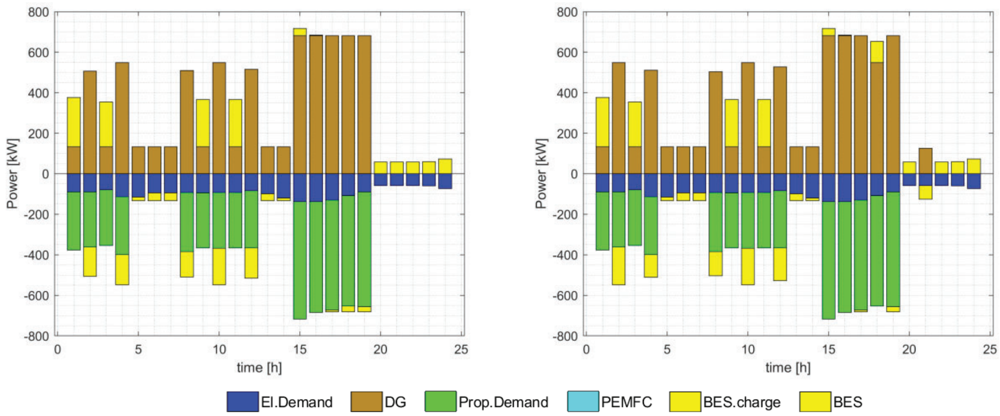


Figure 4 – Electrical load profile solutions for current scenario for mild (left) and cold weather (right).

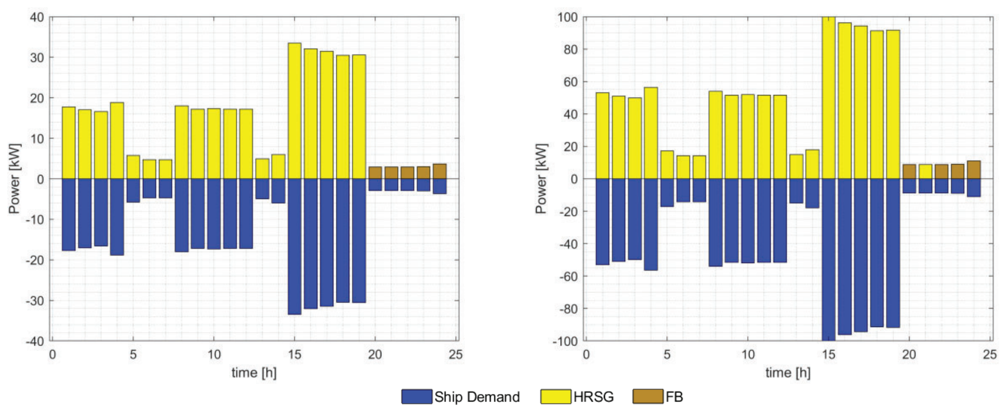


Figure 5 – Thermal load profile solutions for current scenario for mild (left) and cold weather (right).

Analysing the results, it can be observed that the batteries are used to operate DG technology as close as possible to the optimum point, in order to maximise the efficiency of the system by decreasing both consumptions and emissions. Regarding the thermal demand, HRSG units from DGs heat waste are used whenever possible. This technology requires a considerably higher investment compared to the fired boiler solution; however, it is justified by the fact that it saves fuel and reduces emission taxes. Turning on a fired boiler is necessary when demand is below the technical minimum.

3.3. Near future scenario optimal solution

This section presents the results of a simulation using a near future scenario, characterized by CO_2 tax [23] 100€/tons and hydrogen cost 1.5 €/kg, according to recent forecasts [25].
The technologies considered by the tool to minimise the objective function are listed in the Table 4 together with the best resulting configuration.

Table 4 - Optimization results, considering the actual scenario.

Supplier	Model	N° of elements installed	CAPEX / FuelCost [€/unit] / [€/y]
		Diesel Generator	
Solè Diesel	SDZ-205	1	35750
Solè Diesel	L1306C2 MSD	1	147500
Isotta Fraschini	SDZ-280	0	-
		Organic Rankine Cycle	

Orcan Energy	eP M 050.100 HP	0	-
Zuccato Energia	ZE-30-ULH	0	-
Proton Exchange membrane Fuel Cell			
Genevos	HPM-15	0	-
Nuvera	E-45-HD	0	-
Nuvera	E-60-HD	1	88500
Battery Electrical Storage			
Corvus Energy	Orca Pack249	0	-
Nidec	Marine battery pack	3	48000
Heat Recovery System Generators			
Siemens Energy	100	2	9900
Siemens Energy	10	1	990
Fired Boiler			
AlphaLaval	Aalbotg CHB	0	-
AlphaLaval	Aalbotg CHB	1	4000
Fuel Considered			
DG:	Heavy Fuel Oil		213810
FB:	Heavy Fuel Oil		
PEMFC:	Compressed green hydrogen		40089
Emissions			
CO_2			152230

According to the results of the tool, it appears that the price drop of hydrogen had a significant influence on the optimal energy mix. In this configuration, a PEMFC of 60 kWe is installed. Therefore, this technology currently has a major weakness: the price of fuel. However, the expected reduction of H2 price in the near future will make it a competitive solution, not only for their zero-emissions, but also from an economical point of view.

As shown by the load profile solution (Figure 6), the tool highlights that PEMFCs cannot be operated at maximum load all the time. This result is due to the SoC of the hydrogen stored in the ship: its energy density is fairly low, so the volume dedicated to hydrogen storage does not allow for a more intensive use of the fuel cells. However, it can be observed in Figure 6 how the fuel cells replace the batteries during the port stays.

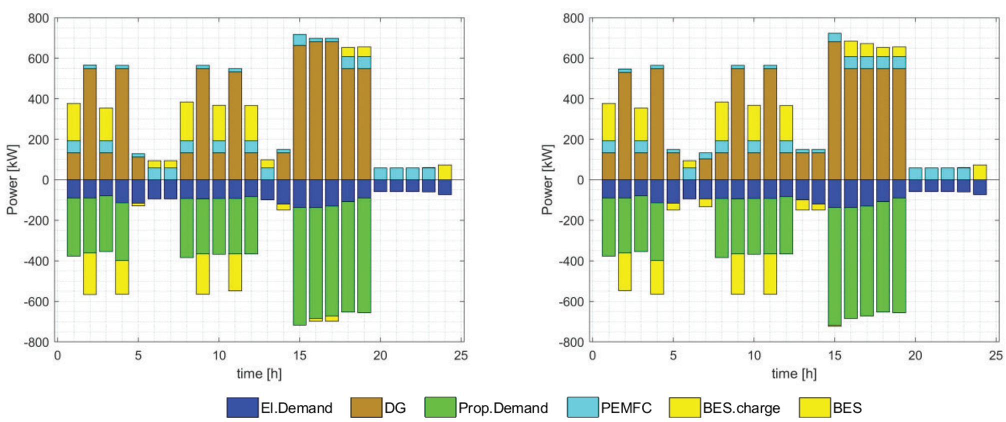


Figure 6 – Electrical load profile solution for the near future scenario for mild (left) and cold weather (right).

Figure 7 shows that the installation of the PEMFCs did not affect significantly the thermal power generation, compared to the results shown in Figure 5 for the current scenario. In fact, the thermal power is mostly supplied by the HRSG, with the FB that is turned on only when necessary.

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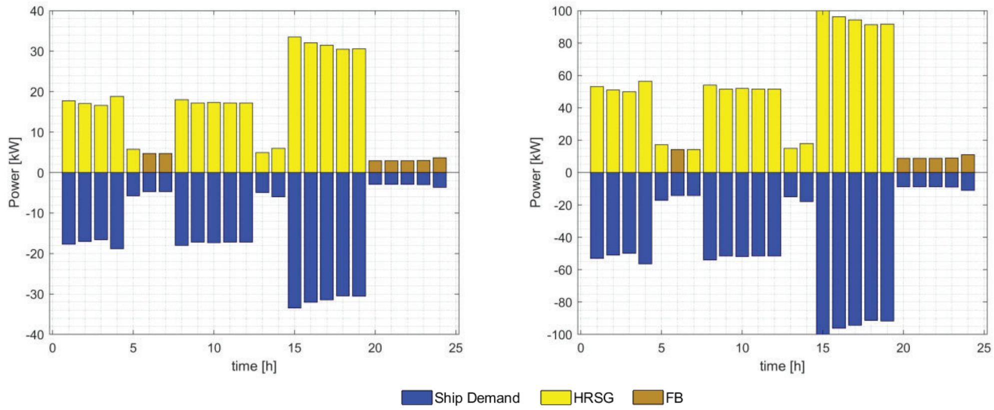

Figure 7 – Thermal load profile solutions for the near future scenario for mild (left) and cold weather (right).

4. Conclusions

This paper presented a MILP model designed to determine the best power generation mix to be installed on a ship and, at the same time, to optimize the operation of each energy system. The MILP model was developed in MATLAB environment relying on the Yalmip optimization toolbox. The model compares different technologies to find the layout that minimizes an objective function, representing the annual costs necessary to cover the electrical and thermal energy demands of the vessel. The analysis is performed considering the specific constraints of the problem, related to the available volume on-board, technical limitations for each technology and overall energy balances (electrical and thermal) to satisfy the demand in each period (hour) of the navigation year. Fixed costs, fuel costs and CO_2 taxation are included in the objective function. The case study of a small passenger ferry boat is considered, taking into account three different representative energy demand profiles, for hot, mild and cold season respectively. Different possible market technologies are considered for on-board installation and electrical (diesel generators, PEMFC, batteries, ORC) and thermal (HRSG, fire boilers) energy production. The following conclusions can be drawn from the results:

- In the current scenario, the optimal configuration mostly relies on traditional and consolidated technologies, i.e. DG and HRSG. These systems are installed and employed to satisfy the largest part of the demand, with a small contribute by electrical batteries.
- In the near future scenario, characterized by lower hydrogen price, PEMFC are installed as well on-board to generate a part of electrical energy. This fact leads to CAPEX increase, but also allows for a reduction in terms of CO_2 emissions and related fees.
- In all the scenarios, the largest costs are due to fuel and CO_2 taxes, which are both strongly dependent on international markets and environmental/energy policies: an increase in CO_2 fees or in fossil fuel prices, or a decrease in hydrogen production cost, can represent one of the key points for economic feasibility of more sustainable solutions.

In the future, the MILP model will be used to assess more precisely the impact of CO_2 taxation on the optimal energy solution. The library of components considered by the tool will be expanded, introducing electric boiler technology as an alternative to HFO-fuelled boilers. This solution expected to further reduce CO_2 emissions.

Moreover, the MILP tool will be tested on different types of vessels, to understand how different sizes and navigation plans change the best power generation strategy.

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 https://doi.org/10.52202/069564-0131

Appendix A

Table A.1. Database of main technologies implemented and available in the tool.

Diesel Generators

Supplier	Model	Brake Power (max-min) [kW]	Efficiency (max-min) [%]	Kcost [€/kW]	Kgrav [t/kW]	Kvol [m^3/kW]	Useful Life [y]
Wartsila	8L25	3000-900	55-30	250	0.0089	0.0167	25
Wartsila	8V31F	4880-1464	55-30	250	0.0117	0.0184	25
Wartsila	10V31F	6100-1830	55-30	250	0.0106	0.0163	25
Wartsila	14V31	8540-2562	55-30	250	0.0099	0.0163	25
Wartsila	16V31	9760-2928	55-30	250	0.0095	0.0154	25
Wartsila	8L46F	9600-2880	55-30	250	0.0129	0.0108	25
Wartsila	12V46F	14400-4320	55-30	250	0.0123	0.0155	25
Wartsila	14V46F	16800-5040	55-30	250	0.0129	0.0191	25
Wartsila	16V46F	19200-5760	55-30	250	0.0121	0.0184	25
Rolls-Royce MTU	12V 4000 P63	1350-405	55-30	250	0.0054	0.0062	25
Rolls-Royce MTU	16V 4000 P63	180-540	55-30	250	0.0049	0.0055	25
Rolls-Royce MTU	20V 4000 P63	2245-674	55-30	250	0.0048	0.0051	25
MAN	14V51/60DF	14700-4410	55-30	250	0.0151	0.0199	25
Isotta Fraschini	V1712C2 MLH	1350-405	55-30	250	0.0034	0.0062	25
Isotta Fraschini	V1708C2 MLL	815-245	55-30	250	0.0044	0.0061	25
Solé Diesel	SDZ-280	200-60	55-30	250	0.0034	0.0056	25
Solé Diesel	SDZ-205	143-43	55-30	250	0.0045	0.0076	25

Organic Rankine Cycles

Supplier	Model	El.Power Output (max-min) [kW]	Efficiency (max-min) [%]	Kcost [€/kW]	Kgrav [t/kW]	Kvol [m^3/kW]	Useful Life [y]
Zuccato Energia	ZE-30-ULH	30-15	8.5-4	2500	0.103	0.323	15
Zuccato Energia	ZE-40-ULH	40-20	8.9-4	2500	0.078	0.243	15

https://doi.org/10.52202/069564-0131

Zuccato Energia	ZE-50-ULH	50-25	9.1-4	2500	0.090	0.206	15
Zuccato Energia	ZE-100-ULH	100-50	8.3-4	2500	0.065	0.348	15
Orcan Energy	eP M 050.100 HP	100-50	9-4	2500	0.023	0.033	15
Orcan Energy	eP M 150.200	200-100	9.5-4	2500	0.023	0.037	15

Proton Exchange Membrane Fuel Cell

Supplier	Model	El.Power Output (max-min) [kW]	Syst.Efficiency (max-min) [%]	Kcost [€/kW]	Kgrav [t/kW]	Kvol [m^3/kW]	Useful Life [y]
Ballard	FCWave	200-55	40-53.5	50	0.0050	0.0098	10
Nuvera	E-45-HD	45-13	37-50	50	0.0042	0.0067	10
Nuvera	E-60-HD	59-16	40-53	50	0.0032	0.0051	10
Ned Stack	PemGen MT-FCPI-100	100-28	37-50	50	0.0250	0.0462	10
Ned Stack	PemGen MT-FCPI-500	500-138	37-50	50	0.0300	0.0858	10
Powercell	Marine System 200	200-55	45-60	50	0.0035	0.0063	10
Proton Motor	HyShip	213-59	40-50	50	0.0035	0.0063	10
Genevos	HPM-40	40-11	40-52	50	0.0048	0.0130	10
Genevos	HPM-80	78-22	40-52	50	0.0042	0.0115	10

Battery Energy Storage

Supplier	Model	Capacity [kWh]	El.Power Max (Charge-Discharge) [kW]	Efficiency (Charge-Discharge) [%]	Kcost [€/kWh]		Kgrav [t/kWh]	Kvol [m^3/kWh]	Useful Life [y]
Corvus Energy	Orca Pack249	249	747	70-80	400	0.013	0.011	10	
Corvus Energy	Orca Pack992	992	2976	70-80	400	0.013	0.011	10	
ABB	containerized ESS	1100	1100	70-80	400	0.027	0.049	10	
ABB	eStorage Flex 10-190	190	160	70-80	400	0.028	0.114	10	
ABB	eStorage Flex 10-240	240	160	70-80	400	0.024	0.090	10	
Nidec	marine battery pack	120	120	70-80	400	0.007	0.007	10	
Forsee power	Pulse15 146	146	572	70-80	400		0.018	0.017	10
Forsee power	Pulse15 219	219	857	70-80	400		0.018	0.017	10

https://doi.org/10.52202/069564-0131