Effect of different propulsion systems on CNG ships fleet composition and economic effectiveness

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Abstract. The compressed natural gas (CNG) transport is becoming nowadays an attractive solution not only for stranded gas shipping where current technologies like liquefied natural gas (LNG) and pipelines are not economically competitive, but also for long-enough distance transport of large volumes of natural gas, where LNG still represents the most economical solution. In fact, recent studies on pressure vessels (PV) materials allow to significantly reduce the ship displacement in case of PVs Type 3 and Type 4 when compared to existing prototype designs with PVs Type 1 and Type 2, also leading to completely different hull forms. Since CNG ship design is a new research field for Naval Architecture, the concept design phase assumes an utmost importance with respect to design of well-known ship types, not only for the main parameters determination and performances assessment, but also for the study of completely different solutions for some subsystems. To this purpose, the present paper presents a technical-economic comparison between two different kinds of propulsion systems: conventional diesel drive propulsion with propellers and a complete diesel electric solution with pods. The differences between the two solutions are influencing both internal layout and ship dimensions, leading to two completely different ship concepts. These have been compared to determine the most cost effective solution not only for the single CNG ship but mostly for the fleet composition in a given transport scenario.

Keywords. CNG ships, propulsion system, hull forms, optimal fleet composition

1. Introduction

The increasing interest to reach more flexibility in the exploitation of natural gas resources [1], imply to focus the attention also to the transportation of the hydrocarbon from off-shore fields to on-shore installations [2]. On this purpose, besides traditionally adopted transportation by means of pipe lines or liquefied natural gas (LNG) ships, the compressed natural gas (CNG) transport solution is becoming nowadays really attractive [3]. Due to the continuous research on the pressure vessels (PV) materials [4], CNG solution is starting to became economically competitive also on determined long distance

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transport of large hydrocarbon volumes, where traditionally LNG has always been the most economical transport solution. Being CNG effective also for stranded gas shipping, it is the opinion that in the present future, CNG technology will be the most flexible solution for natural gas transport.
On this purpose, the selection of an optimal fleet [5] for CNG transportation becomes of primary importance. Alternatively, the best CNG ship model [6] can be identified, in order to find the most cost effective solution [7].
The present work is aimed to provide a first investigation over the propulsive system impact on the total cost effectiveness of a CNG fleet in a given transport scenario. In the specific a conventional propulsion system with 2-stroke engines has been compared with a fully diesel-electric solution with pods. The considered scenario refers to the gas transportation in the Mediterranean area, considering the adoption of a Type 3 PV's technology for the gas storage on-board.
Through this paper, a description of the two different propulsive system will be given, considering the differences that this choice will have on the ship's aft-body and general layout. Considering than two distinct meta-models for the two ship types, two optimal fleets have been determined for the selected scenario according to predefined financial and economical considerations [5]. As result the shipping tariff of the two proposed solutions have been compared to give a judgement on the best solution achieved for the selected scenario. Besides, also the two ships, composing the best fleets, are compared, highlighting the differences in terms of hull forms, internal layout and propulsive performances.

2. Propulsion systems

Since CNG ships design is a field in early exploration, no sure guidelines are present on the effect of different propulsive systems installation on the global effectiveness of the design. In the present work a comparison has been done between a conventional propulsion with 2-stroke diesel engines and a full diesel electric solution. The composition of the propulsive system is really different and will influence not only the aft-body and propeller design of the ship, but also the general arrangement. This is a crucial aspect that should be considered starting from conceptual design stage. In this section a brief description of the two systems will be given, together with the differences that will rise up in the conceptual modelling of the ship.

2.1. 2-stroke diesel engine system

A possible solution to be investigate for the ship propulsion is the adoption of a conventional propulsion system, adopting 2-stroke dual fuel engines as prime movers. In fact, such kind of solution imply the utilisation of high efficiency motors, rotating at low speeds that can be directly coupled with the propeller. In such a way all the propulsive drive will be extremely essential, reducing the amount of losses from engine brake power to propeller delivered power.
However this kind of propulsion system requires a propeller rotating also at low speed, typically no more than 124 rpm for the smaller engines. Such a low rotational rate imply the utilisation of large diameter propellers, being mountable only in case of a sufficiently

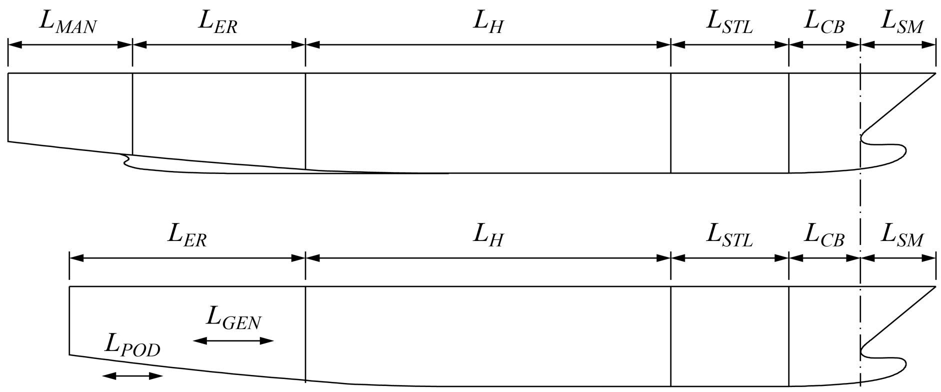

Figure 1. Total length definition for the two proposed ship concepts.

high draught. Because of the adoption of a Type 3 PV, it is not reasonable to presume to have a high draught even for high capacity ships, for such a reason, in order to keep the propeller diameter under control, the selected hull form for this kind of propulsive solution will be of the twin-skeg type.
This kind of propulsive layout requires a different modelling of the propulsion since conceptual calculations. In fact, the optimum propeller selection procedure can be done using a B-Series [8] propeller, but the determination of propulsive coefficient, especially for wake fraction w, is not comparable with a twin-screw ship. The presence of the *gondola* is effectively decreasing the relative flow velocity coming into the propeller disk, leading to values of w more similar to single-screw propellers.

2.2. Diesel-electric system

Another interesting solution for the propulsive system, can be the adoption of a diesel-electric propulsion. In general, diesel electric solution is used when the electric loads on board of the ship are comparable with propulsive ones. This is not the case of a CNG ship during transfer. However, the adoption of such kind of system will allow to install on-board a pod propulsive device, which can be considered as an improving solution for the positioning ability of the ship, essential to increase operability during loading-offloading procedures from a fixed buoy. Besides, the installation of the pods leads to a totally different hull-form for the aft-body, having a shape more similar to a conventional twin-screw ship.
That means the meta-model used for ships generation will be different between the two cases, in order to capture the peculiarities of each potential hull-form.
For this particular propulsive layout, the modelling of the pod-unit (similar to a thruster unit as in [9]) should be done during the propeller selection procedure, for the propulsive coefficient the modelling like a twin-screw ship is accurate enough for a concept phase.

2.3. Consequences for ship's internal layout

The selection of two different propulsive systems will have not only influence in the hull form modelling, so in the way that the hydrodynamic performances should be evaluated,

but also in the internal layout of the ship. Means the propulsive system selection will influence the areas needed to fit the engine room and consequently the main dimensions of the ship. As described in [10], the internal layout modelling of a CNG ship can be done as function of the so-called *primitive cargo unit*, that for the case under analysis is the PV diameter. On the basis on that all the internal dimensions for the hold can be determined in such a way to determine a required cargo space. Besides holds volume, also bow and stern overhangs should be modelled, ensuring enough space for the engine room and for the manoeuvring system.
The two different configurations require a different modelling of the stern area, means the two ship concepts will have different lengths at equal holds capacity. In Figure 1 a schematic representation is given of the different configurations. As it can be seen no differences are needed for the fore part of the ship.
With such a kind of discretisation, considering the system origin on the fore perpendicular, the length overall L_{OA} definition becomes:

$$L_{OA_{twin-skeg}} = L_{SM} + L_{CB} + L_{STL} + L_H + L_{ER} + L_{MAN} \tag{1}$$

$$L_{OA_{pod}} = L_{SM} + L_{CB} + L_{STL} + L_H + L_{ER} \tag{2}$$

where L_{SM} is the stem overhang length, L_{CB} is the collision bulkhead position from origin, L_{STL} is the STL space, L_H is the holds length, L_{ER} is the engine room length and L_{MAN} is the manoeuvring machinery space. It must be noted that for L_{ER} determination, in the podded case it includes both the pods L_{POD} and the gen sets L_{GEN} length, being then no necessity to ad an extra space for manoeuvring equipments. The L_{ER} is then function of the machinery size selected by the mathematical meta-model.

3. Optimal fleet composition

To select the optimal fleet configuration a rational scheme has been implemented which integrates a menu of CNG prototype ships into a logistics framework. The key idea in the in-house developed decision-based scheme (DBS) is concurrent consideration of logistics and conceptual designing of ships with simultaneous merging of technical and economic properties. Different strategies, especially whether of sequential nature, can lead to wrong decision making. In other terms, the DBS simultaneously selects the number of ships entering in the fleet together with their size and optimal service speed [5]. A number of parameters and constraints are primary drivers of simulation: loading and offloading rates per day, distance to the market, connecting and disconnecting time on terminals, stand-by time. The final selection of the optimal fleet composition is ruled by searching for the minimum shipping tariff. The optimal fleet composition has to guarantee a continuous delivery to the destination terminal, being flaring and re-injection not allowed. The selection of the best fleet is carried out by ranking for the minimum tariff asked the oil & gas company on an annual basis to transport a volume unit of compressed natural gas. The optimal fleet composition has to guarantee a continuous delivery to the destination terminal. The selection of the optimal fleet is carried out by ranking for the minimum tariff asked by the supplier on an annual basis to transport an energy unit of compressed natural gas (USD/mmBtu).

3.1. *The families of CNG ships*

The design of competitive CNG ships presents a number of formidable challenges, which include safe loading and unloading gas system, as well as the tight integration of gas containment system, structure and propulsion. These difficulties are compounded by lack of existing baseline ships, historical databases, and compressed gas experience within the design community. Consequently, designers must rely on physics-based analysis methods that facilitate rational decisions and compromises.
To this end, a mathematical design model for CNG ship mimic was developed and inserted into a multicriterial decision-making support system. Since CNG ship concepts are prototypes, inadequate information about configuration and size of feasible designs is overcome by generating efficient (Pareto) solutions where the preferred designs are selected with fuzzy ELECTRE method [11].
Two families of CNG have been built off-line at a level sufficient at concept design stage: the former with twin-skeg hull form; the latter with a pod propulsion system. each family comprises 19 ships with CNG capacity raging from 50 to 950 mmscf The main topics included in the design mathematical model needed to assess the primary properties (attributes)of each candidate ship in a random generation of concept designs, are the following:

- identification of main dimensions and geometrical coefficients viable to install the pressure vessels adequate to transport the required volume of CNG;
- selection of length of pressure vessels with given internal and external diameter under the following crisp constraints: compliance with intact and damage stability rules, roll period greater than 13 s to avoid resonance between roll and wave periods, and avoidance of coupling lateral and vertical motions;
- assessment of midship section structure and lightship weight breakdown;
- power prediction in calm water and in a seaway;
- analysis of intact and damage stability for compliance with IMO rules;
- electric power balance;
- seakeeping assessment for added resistance, motions and accelerations;
- powering and gas consumption prediction at different speeds in a round voyage (cycle);
- total time to perform a cycle;
- one-dimensional vibration calculations to avoid risk of resonance between main modes of hull vibration and propellers speed;
- round-trip modelling;
- horsepower for compression on-board to unload gas and simultaneous stand-by (dynamic positioning)

3.2. *Shipping tariff estimation*

Only shipping tariff is here estimated. Absolute values of tariffs should be read cautiously, since building cost of each ship is evaluated according to average hourly cost and productivity of Italian shipyards, whilst daily operating costs are derived from average data for LNG ships, gas costs at well-head are set from present market information. Basically, a discounted cash flow model under assumed financial scenario is used to solve for tariff. It involves identification of key elements which determine the investment

outcomes, such as ship acquisition and operating costs, tax and interest rates, leverage scheme, economic life, salvage value, etc. In the following, discounted cash flows are calculated on an after tax basis.
The following are key considerations in tariff estimations:

- terms of Project assumed as 15 years;
- levered investment capital with 60% loan, 5.5% interest rate, and 10 years for loan repayment period;
- *Capex* includes ship capital expenses spread over three years prior to first gas delivery, where shipyard overheads are assumed as 30% of overall labour cost, and expected net profit for shipyard is assumed at 6.5% after taxes;
- *Opex* includes: ship operating expenses (dry-docking, M & R, crew, etc.) escalated at 2% per annum starting from first gas delivery, where natural gas cost is estimated at wellhead price USD 2.95/mscf, averaged on the last year data;
- linear depreciation of ship value taken as 17.5% after 15 years of ship lifetime;
- Tax Rate: the NPV of discounted cash flow is assessed with corporate tax rate of 30%;
- Internal Rate of Return for the ship owner is assumed as 12% as expected project return.

4. Operative scenario

Application of the implemented model is limited here to analysis of the viability of the marine CNG transport from an offshore loading terminal to an offshore unloading terminal (hub-and-spoke distribution pattern) with a source-destination distance of 1,000 nm and a production rate as 2 billion cubic meters per year.
Prior to determine the optimum fleet composition for both the families of CNG ships, which differ because of the different propulsive options, it is necessary to define the operative scenario to be considered for the simulations.
In determining the composition of feasible fleets, e.g. number of ships in the fleet, size and capacity of each sister ship, resulting shipping tariff at each speed (17-24 kn at 1-knot step) the following parameters are set:

- connect/disconnect time: 1.5 hours for each operation;
- stand by-time needed to consider unpredictable situations and to round up each one-way voyage to the nearest half a day time, set at 8.5% day;
- 355 operating days per year.

As a result of the optimal fleet composition, also the best ships characteristics composing the fleet can be evaluated.
Figure 2 illustrates a number of feasible fleets for the given operating scenario for both the two families of ships. For each feasible fleet, it can be easily identified the optimal service speed which is singled out by the lower shipping tariff. For the twin-skeg solution, the optimum corresponds to 6 ships sailing at a service speed V_{srv} of 23 knots, resulting in a total gas capacity of 290 mmscf. The podded solution, for the analysed case, presents less evidence for the optimum determination. In fact, there is a range of ship capacities yielding fleets requiring almost the same shipping tariff. A reason for this relatively ambiguous behaviour can be found in the discontinuous pod and dual fuel gen-sets

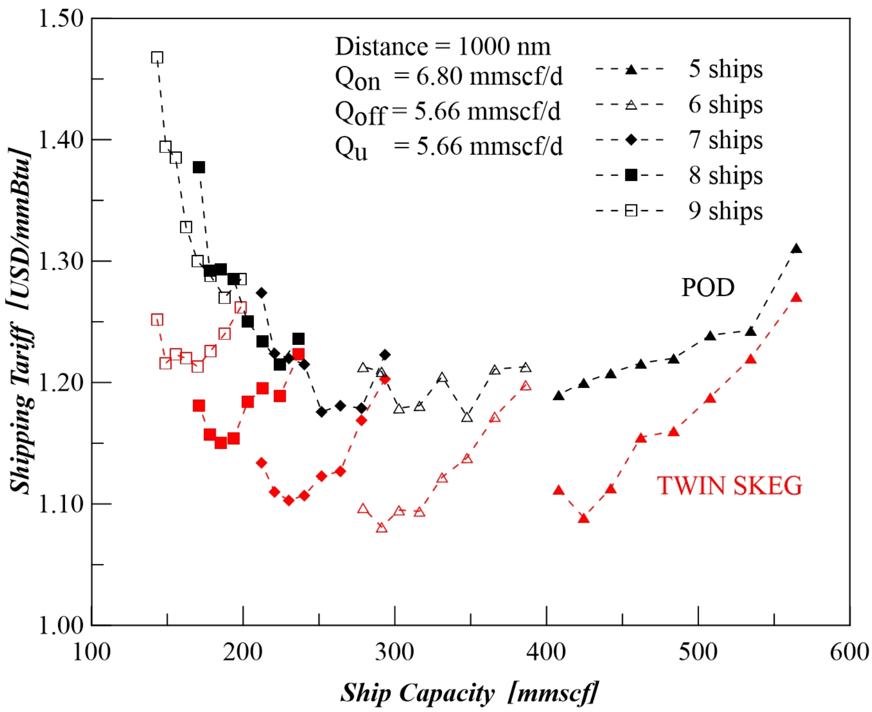

Figure 2. Shipping tariff for different fleet solutions considering twin skeg ships (*red*) or podded ships (*black*).

sizes available on the market. On base of this consideration, the solution corresponding to the absolute minimum shipping tariff has been selected, resulting in a fleet of 7 ships with V_{srv} of 20 knots and a capacity of 251.6 mmscf.

It is worth noticing that the optimal speed generally increases when the number of ships in the fleet decreases.

5. Selected ships comparison

As result of the optimal fleet composition, also the best ships characteristics composing the fleet can be evaluated. The adoption of dedicated meta-models for the parameter identification of the two proposed concepts, allows to evaluate the ships characteristics in terms of dimensions, capacity, propulsive power, seakeeping behaviour and vibrations.

Having determined two optimal fleets composed by ships with other capacities and service speeds has yielded to the determination of two totally different ships, not only for the propulsive system, but also for the global dimensions. In Table 1 a summary of the main characteristics of the two vessels is reported. analysing the main dimensions and the coefficients, it rises immediately up that the twin-skeg solution, even though is bigger than podded ship, is more slender than the other. This is essentially due to the necessity of the ship to sail at an higher speed than the pod one. In fact the twin-skeg solution should have a service speed V_{srv} corresponding to a Fn 0.26, while V_{srv} for the podded one is referring to Fn 0.24. The fact that, due to the economic scenario, the two ship concepts should have different ratios between total displacement and delivered cargo, even

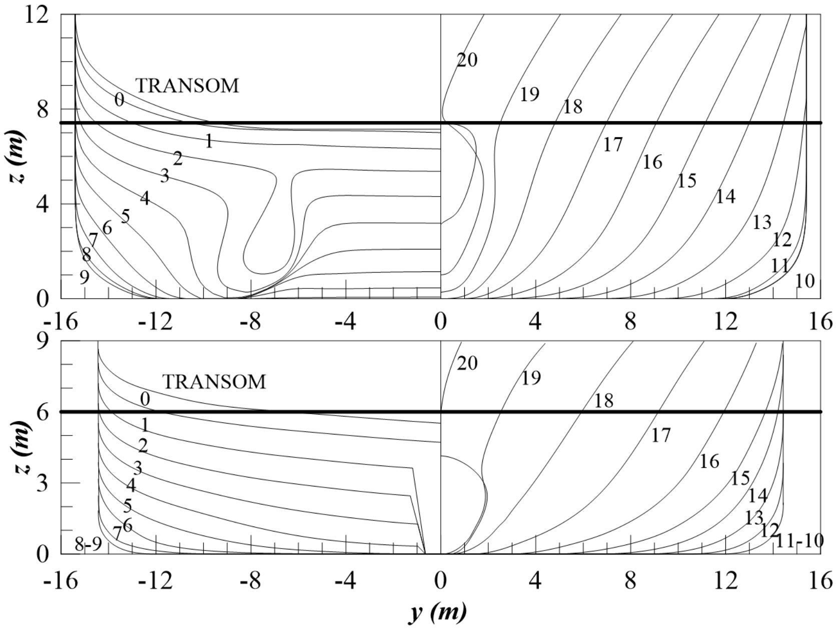

Figure 3. Body plan of the twin skeg ship (*top*) and podded ship (*bottom*).

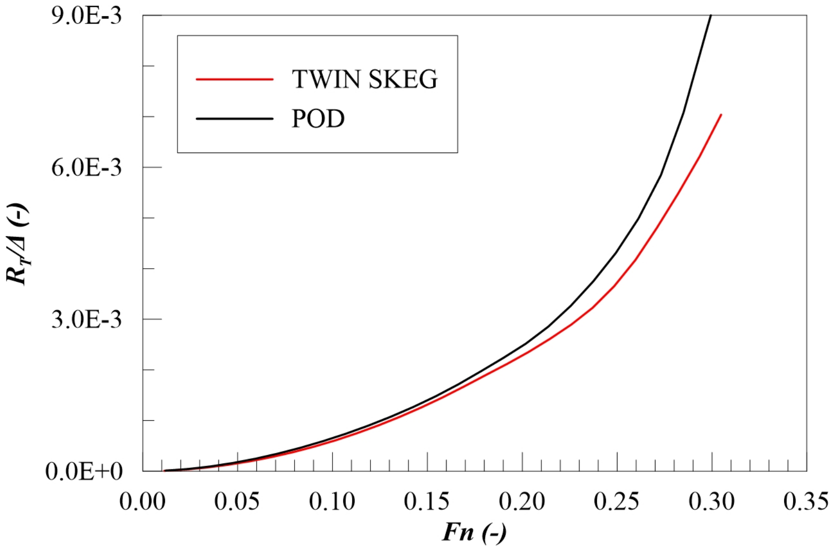

Figure 4. Specific resistance as function of Fn for the two ships.

increases the differences in terms of block coefficients for the two ships.

Considering the two ships databases used for the meta-models determination, it is possible, by adopting a procedure as described in [10], to determine a preliminary body-plane for the two proposed solutions. In Figure 3 it is possible to observe the differences in the two resulting twin-skeg and podded hull forms. Here it can be seen that the podded hull

Table 1. Main particulars of the two ship concepts.

		Twin-skeg	Pod	
Length over-all	L_{OA}	216.82	200.20	m
Length between perpendiculars	L_{BP}	201.02	185.60	m
Breadth	B	30.82	28.86	m
Design draught	T	7.42	6.00	m
Volume of displacement	∇	27950.3	22304.5	m^3
Prismatic coefficient	C_P	0.622	0.710	–
Midship coefficient	C_x	0.978	0.978	–
Waterplane area coefficient	C_{WP}	0.830	0.886	–
Service speed	V_{srv}	23.0	20.0	kn
Available shaft power	P_S	22304.5	19601.0	kW
Propeller diameter	D	4.800	4.350	m
Pitch diameter ratio	P/D	1.325	0.874	–
Expansed Area ratio	A_e/A_0	0.634	0.598	–
Blades number	Z	4	4	–
Ship capacity	∇_g	290.0	251.6	$mmscf$
Number of PV	N_{PV}	305	287	–
Length of PV	l_{PV}	25.40	23.20	m
Delivered gas per cycle	w_{gd}	4576.9	3945.8	t
Gas consumption for propulsion	w_{gc}	211.6	168.1	t
Cycles per year	$c_{p.y.}$	51.5	50.0	–

form is characterised by a parallel middle-body covering sections from 8 to 11, while for the twin-skeg, it is restricted to the sections between 9 and 10. With all these considerations, it is reasonable to presume that the hull of the twin-skeg will have a better specific resistance compared to the pod solution, this can be seen in Figure 4, where is evident that the podded ship has the worst specific resistance through the whole speed range.
The same consideration is still valid when propulsive issues are considered. In fact, analysing a ideal trial condition for the two vessels, the following prediction can be made for the two ships considering the propulsive power mounted on board of each configuration as per Table 1. For twin-skeg concept, mounting a propeller with geometrical characteristics similar to the one of Table 1, a sustained speed of 24.45 knots is expected with propellers rotating at 124.0 rpm absorbing a shaft power of 22304.5 kW without presence of wind and waves. Under the same conditions, a speed of 21.55 knots with propeller rotating at 203.8 rpm with an available shaft power of 19601.0 kW is expected for the podded solution. It must be noted that the selected propellers parameters have been chosen, considering the service speed of the ships as design point, taking into account a sea margin of about 20% with respect to calm water conditions. The results of the speed power predictions for trials have been reported in Figure 5. Here it can be seen how the propulsive curve for the podded solution, is rapidly becoming steeper after the 21.5 knots. That is due to the rising up of cavitation problems, witch are drastically increasing the propeller revolution rates and consequently the absorbed power.
Besides pure hydrodynamic considerations, it is interesting to analyse the two different internal layouts coming from the conceptual design phase. As mentioned, the developed design method is suitable to analyse the internal layouts on the base of the *primary cargo units*, fitting the most suitable holds configuration for the ship's dimensions. In Figure 6

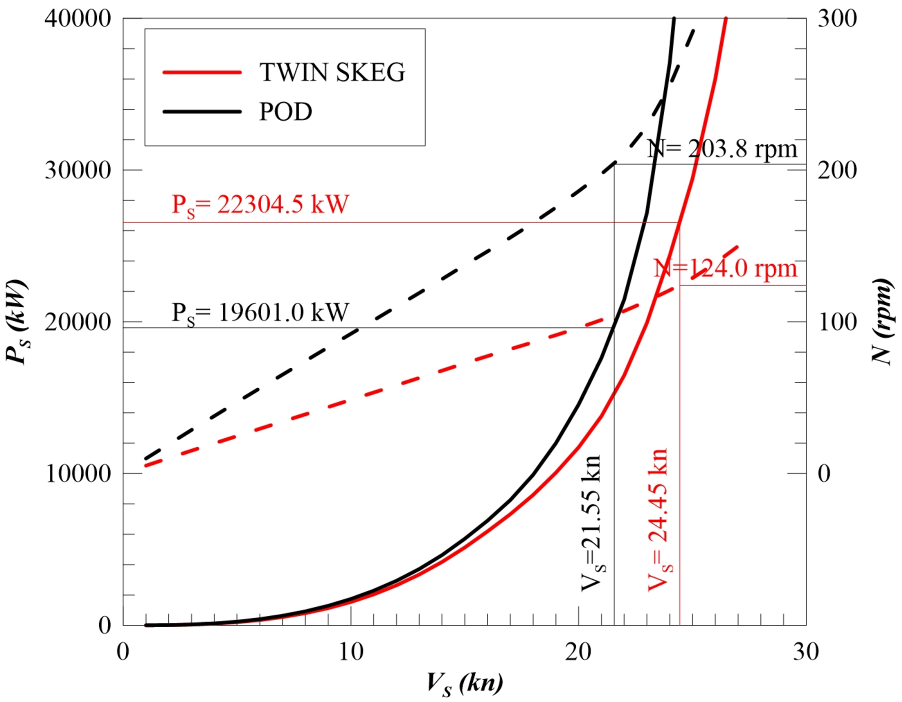

Figure 5. Speed power prediction at trials condition for the two ships.

it is possible to visualise the two resulting conceptual general arrangement. Both vessels have a cargo space subdivided in 5 holds, but the number of PV per hold is different. The transversal number is 9 for the two versions, since the differences in breadth between the two units did not allow the installation of an additional PV for the twin-skeg case. However the number of lines is different, being 7 for the podded solution and 8 for the twin-skeg. it is also interesting to notice how the holds are disposed. The podded vessel,having a relatively bigger parallel middle body, is suitable to have almost 4 fully loaded holds; on the contrary, twin-skeg solution is having only three holds fully loaded, while the foremost two are strictly limited by the fore-body shape.
It can also be noted that the propulsive system got also an influence in the general arrangement. In fact, the engine room for the podded ship case is less extended compared to the twin-skeg solution, leading to a much shorter aft-body.

6. Conclusions

The two analysed propulsive solutions on family of CNG ships, highlights two distinct optimal fleet compositions for the considered operative scenario, representative of a typical gas transport chain in the Mediterranean Basin.
The resulting shipping tariff seems to privilege the twin-skeg solution, being around 10% less, compared to diesel-electric one. This is essentially due to the higher propulsive efficiency (coupling between hull and propulsors) reached with the conventional propulsive system. The accuracy of the conceptual solutions is well supported by the developed

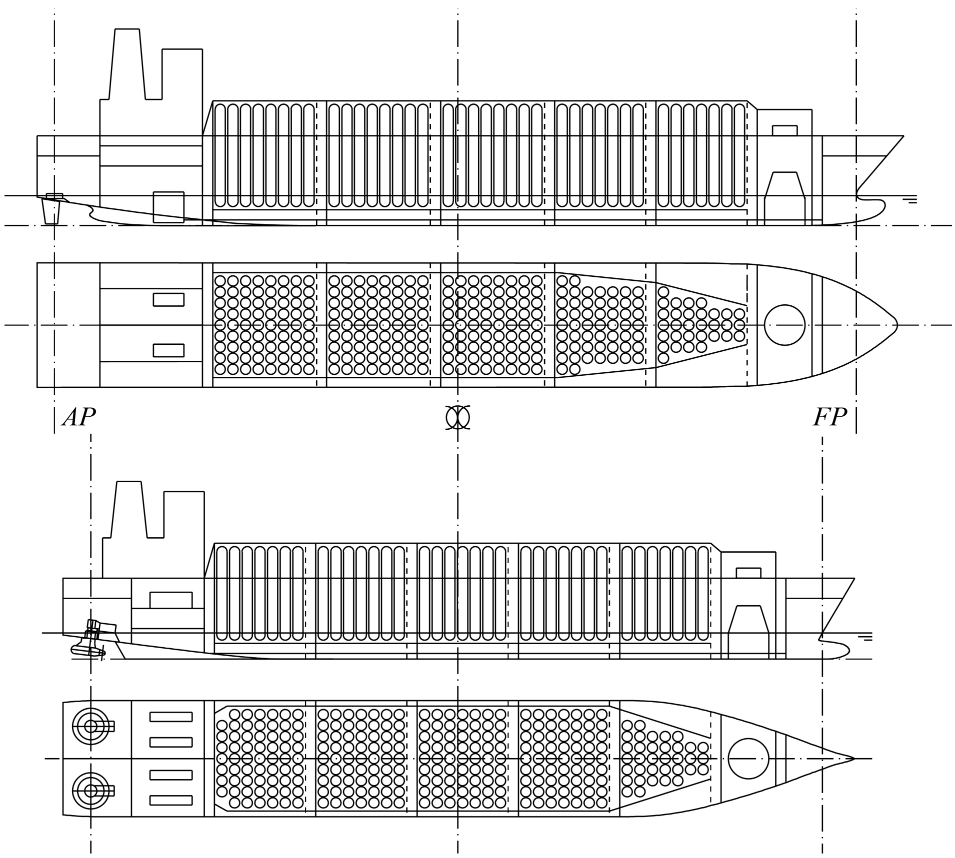

Figure 6. Conceptual general arrangement of the twin-skeg (*top*) and pod (*bottom*) solutions.

procedure capable to generate a preliminary lines-plan and general arrangement.
Further investigation is necessary to evaluate the two propulsive concepts on different operative scenarios, i.e. considering different distances, gas production and loading-offloading rates as well as different considerations of gas storage at both start and ending point of the transportation route.

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