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Adoption of lib (Lithium Batteries) for hybrid propulsion on small passenger vessel and consequences on damage stability

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Abstract: Nowadays the Hybrid Propulsion is a reality, increasing its diffusion. The main principle is the storing of energy in battery packs to provide energy for the propulsion system of the vessel, aiming the fundament of hybrid propulsion is the use of Li-Ion or Li-Po batteries, with high capability of energy storage (MWh). This good capability has the disadvantage of the explosion risk if exposed to heat. The solutions adopted can impact on damage stability. This paper will analyze the aspects connected with hybrid propulsion in small passenger vessels, considering the State of Art of Rules regarding the fire safety and the possible solutions adopted regarding Lithium batteries. The paper refers to the consequences of adoption of new technology of Lithium batteries developed to be used in maritime application, batteries indicated as "LiB". The paper is not referring to Lithium metal batteries with the Lithium used as metallic anode and all the consequences on fire risks. The paper is not about the risk of fire due to the battery technology, but is related to the consequences on stability of small vessels if, for security reason a large amount of water is used to cool down the battery packs. The paper will consider the case study of a small passenger ship, examining the general arrangement adopted and the position of the batteries, and the consequences caused by the installation on board of the battery packs. The results will show how the fire safety is important and requires special attention, also in consideration of the various possibilities to contain the fire or prevent the risk of explosion. The aim is to give a suggestion for set new standards for firefighting in presence of large batteries and also to focus on possible problems arising in case of fire on hybrid vessels.

Keywords: *Damage stability, Firefighting, Hybrid propulsion, Lithium ion lithium polymer batteries, Passenger ferries; Small vessels.*

1. Introduction

Hybrid propulsion is becoming the trend solution for the propulsion of small passenger vessels used for internal water ferries, or for coastal transportation [1-2]. The main goal is the reduction of the pollution, in terms of both chemical pollution and noise, so the combined use of batteries, diesel generators and managenment of both systems can be the answer. The reduction is even more important if we consider that small passenger vessels are adopted for transportation in areas of historical or environmental interest: lakes, rivers, laguna. In all those areas there is often proximity of houses, hotels, etc with the piers and mooring areas. (see Figure 1)

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Figure 1.
Port on Lake for public ferries (Image from CC).

The Hybrid Propulsion is based on the installation on board of a pack of batteries to provide the energy, the solution is not new, was used in submarines and in the first boats in the past but the progress in batteries etc made this more usable.

The fire safety for batteries onboard has already been studied but in case of Hybrid Propulsion the main and new difference is a consequence of the increase in size of batteries. The sizes of normal batteries used for electronics and/or starting batteries for engines is completely different from the sizes of batteries used for hybrid propulsion, in terms of energy stored (kWh) and voltage (V).

The LiB batteries nowadays are very competitive in terms of energy storage, but the criticity is their behaviour when exposed to overheating and fire is well known.

It is already known that there is a substantial difference among Lithium based batteries and the articles refers mainly to the new technology of Lithium batteries developed to be used in maritime application. It is important to understand clearly this difference because the generic “Lithium batteries” could be misunderstood referring to Lithium metal batteries with the Lithium used as metallic anode and all the consequences on fire risks, but this will not be the case studied, as explained in literature cited the batteries considered will be usable for ships, submarines, etc.

As consequence of the above the fire protection has to be reconsidered, studying new solutions. As described, the most used solution is the electrical system, [3-5]: using the principle that the energy stored in the batteries will be used to operate the propellers [6-11].

The increased performances of batteries and also the reduction of the price of LiB batteries (more than 50% in few years) made possible to spread the use of Hybrid propulsion.

The traditional performances of tradition Lead acid batteries have been overcome by the new the Li-Ion batteries, and the advantage in both performances and price reduction is still increasing.

All these factors made possible to realize ships, like the one considered, with a hybrid system of propulsion.

The problem of fire risk on board has been largely underestimated in the past, due to the experience in the constructions of batteries system, but the recent accident, like the sinking of “Felicity Ace”, and further requests from companies operating ferries like on “Havila Kisruten” ferries show that the main problem is the possibility that a fire occurs on board for external reasons of the inner security of the battery system and the risk of overheating must be faced,

2. State of Art of Fire Safety System

This paper aims at examining the new design of fire protection due to the presence on board of a large battery pack, with more than 0.1 MWh capacity, and actual situation of the study and the solutions that battery manufacturers and naval architects studied regarding the risk of explosion if batteries are exposed to heat when a fire occurs on board. The possible solutions adopted will affect the design of the ship, introducing a "new case" not yet examined by the rules.

The paper will examine the problem as an aspect of naval architecture, not considering the electrical design of the system, considering that all the **necessaries'** devices to protect the electrical system by electrical problems like short circuit etc. are already in place and studied by the electrical part manufacturer.

The author already studied the possibilities to modify the General arrangement of a small passenger vessel of similar characteristics [12], and this paper will investigate with more calculations the effects on the intact and damaged stability.

As studied by several authors [13-15], in case of fire, the main danger of LiB is the tendency to overheat and explode. This because, even if there is no direct flame exposition, the batteries remain "active" and if in one cell the temperature rises an explosion can occur and propagating to other cells.

This danger nowadays is well known for hybrid cars [16-17], and one common recommendation by several Fire Departments and also manufacturer of the cars is the submerge the car with water in an appropriate pool, for enough time to cool down the battery pack and reduce the overheating risk.

Obviously, the procedure is not realized during the fire, in case of cars accidents, but after the accident, simply as a measure to cool down the battery cells. As well-known then the ships are surely provided with a firefighting system, using different means ad gases or high-pressure water, but those systems work to immediately extinguish the fire, not to prevent the risk of battery overheating. As already declared the possible causes of the fire on board are not the topic of this paper, who assume that the battery system installed in the ship, will have already all the proper devices to manage the risk of fire caused by the battery system itself, but the paper wants examine the aspect of Naval Architecture, possible solutions to prevent overheating of battery packs in case of a fire on board and consequences on stability in case of extreme need to flood a compartment to cool down the battery packs.

The problem of fire extinguishing on a Lithium battery has been largely studied, and this paper is based on the assumption of installing batteries already studied for maritime use, where the use of water to cool down is possible. Several authors [13-16] also with specific analysis of maritime use [14] emphatized the importance to reduce the temperature of batteries to prevent/extinguish fire.

The majority of battery manufacturers [15] suggest the possibility to use water as a fire extinguisher agent.

The above premises, in an emergency situation like fire on board, with the need to prevent risk of explosion caused by the overheating on battery pack lead to consider the possibility of flooding the battery compartment to secure the battery pack.

The accident occurred on the Norwegian hybrid ferry "Ytterøyningen" in October 2019, can be taken as a sample of the importance of safety on board hybrid ferries and to study carefully the solutions. Of course, if there is a mechanical damage of the batteries the situation is different from the risk of exposing an intact LiB at a problem of overheating, and it requires a different approach.

It is not examined in this paper the problem of all the security electrical devices like circuit breakers etc. to secure the batteries according to the aiming at a naval architecture approach only.

For the ships there is not yet an official solution proposed by the Rules to solve the problem of secure from overheating the battery packs in case of fire on board. The possible solution studied, in according with the rules adopted for the cars, is the flooding of the compartment where the batteries are installed in order to keep the temperature as low as possible, but this flooding, especially on small vessel, can have a deep impact on stability.

The impact of stability is more regarding the naval architecture because is caused by the positioning of the battery compartment, his volume, and consequent solutions adopted.

3. General Description of Case Study

The case study considered in this research is a small ship, a passenger vessel with propulsion realized combining traditional azimuthal propellers operated directly by electrical motors, with diesel generators or LiB batteries to create and store electrical energy, offering the choice, for a limited amount of time, to have the propulsion and services with the energy provided by batteries..

The case study derives from the analysis of the requests present in the recent *tenders* for the construction of ships for public shipping investigating other aspects of stability not yet covered by Rules.

The main difference in the project examined in this paper is realized with the propulsion not totally fed by the batteries, but the energy provided by the batteries is an alternative solution to traditional diesel electric propulsion system. With this solution is possible also consider the possibility of a transformation of an existing vessel, with diesel electric propulsion, adding the batteries and the management system.

4. Ship's Description

The project considered in this research was studied respecting different classification rules: *Registro Italiano Navale* "Rules for the classification of Inland waterway", Directive 2010/36/UE and *Registro Italiano Navale* "Rules for the Classification of Ships". The above-mentioned Rules, for the small passenger vessels in Inland waters increased their standards in the last years adding higher standards for parameters and criteria [18], with changes in the general arrangement of the ships, especially regarding hull's geometry, dimensions, compartment distribution of the ship. The main dimensions of the examined ship considered are in Table 1.

Table 1.
Ship main dimensions.

Loa	**32.45**	**m**
Bmax with fenders	7.50	m
T (Full load)	1.89	m
Speed	11.5	kn
Pax	220	

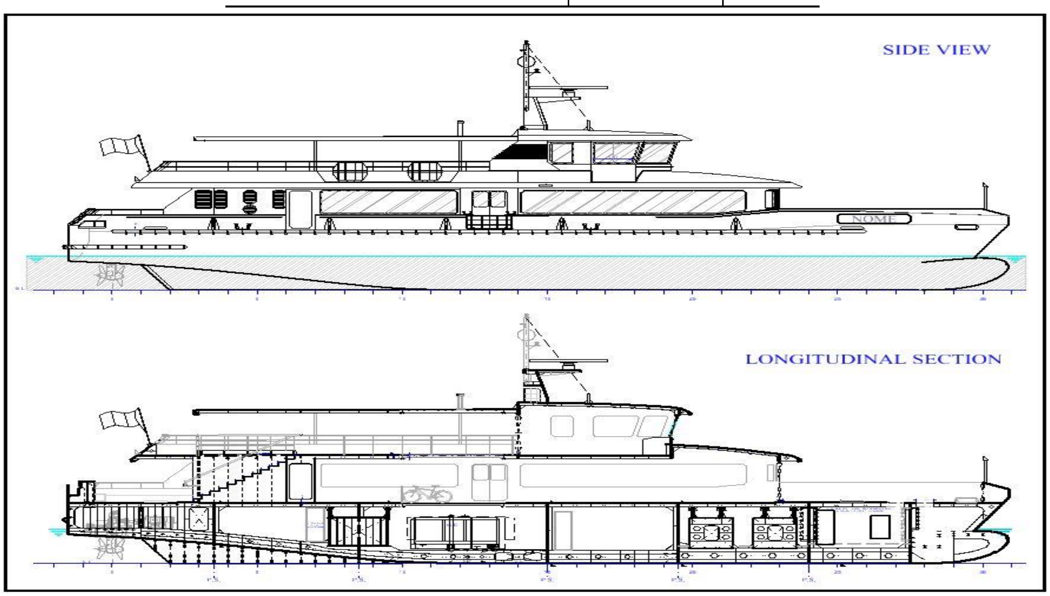

Figure 2.
External view of the Ship 32.45 m ferry.

To define the battery pack capacity and consequentially the range obtainable navigating with batteries has been performed a study of the logistic, route, usage, and consequentially the lay out and the technical choices for the propulsion has been adapted.

As above described, the choice focused on an hybrid propulsion, mainly the source of power during navigation are the diesel generators, with the azimuthal propellers operated by electric motors and the use of batteries for time limited conditions such as silent or zero emission running, to navigate in protected areas or during night time in areas with high density of populations, like the ports on Italian or European lakes.

The main focus is to realize a silent approach, possibly with zero emissions, to the stop pier used for passengers, staying in silent mode during the embarking/disembarking of passengers, and then again move far from pier during the departure.

The main data of the propulsion system, to guarantee the possibility of silent/no emission approach to the pier can be resumed as follows:

Table 2.
Main data of electrical system.

Electrical motors	**2x245**	**kW**
Type of motors	Asyncronous	
Volt/frequency	660/50	V/H z
Technology of batteries (modular)	Li-Po	

As described, ensuring a reasonable degree of protection in case of fire on board, protecting the batteries from the risk of overheathing, requires the study of a new general arrangement, with increase of costs and more difficult the construction, but safer, as it will be shown.

At a first sight the installation of the battery near the GG.EE., reducing the length of electrical cables seems the best option but this solution doesn't give safety in terms of protection from heat because the Engine Room, is usually affected by high temperatures and is considered area at high risk.

As consequence the general arrangement of the vessel has been reconsidered aiming at obtaining more efficiency in term of safety.

The General arrangement of the ship examined, in Figure 3, aims at a smart separation of the main components to deal with the Inland water class, and also aiming at guarantee propulsion also in case of emergency:

The arrangement proposed guarantees the possibility to operate in case of damage of one compartment, maintaining always a degree of independent source of power (GG.EE., battery packs, azimuthal system).

Of course, as good practice of the Naval Architecture, the battery compartment has a A-60 class protection, and all the Machinery compartments are insulated to prevent the risk of heat transmission from one compartment to the other.

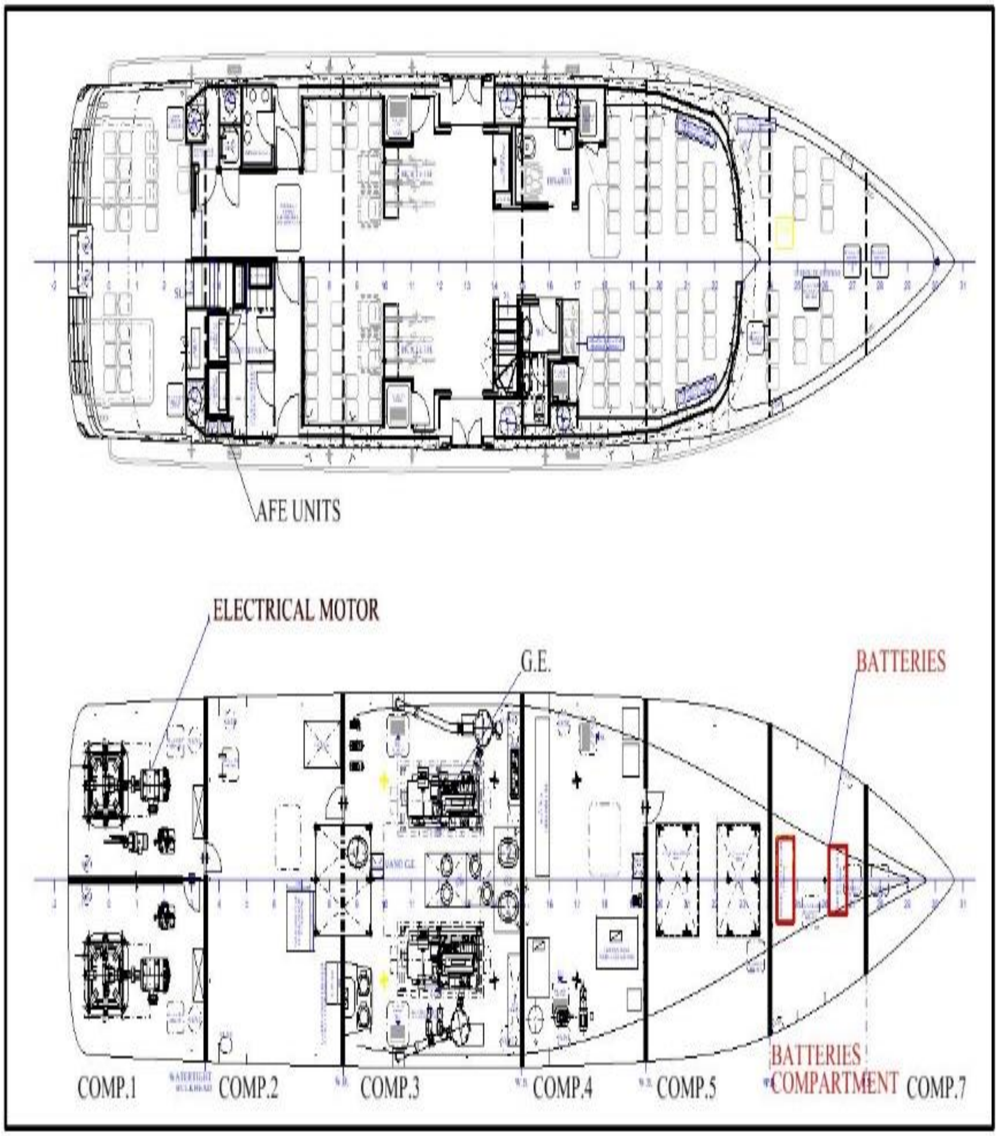

Figure 3.
Proposed general arrangement.

The above-described distribution, with batteries separated from the engines made possible to reduce the risks in case of flooding the battery compartment, in case of damage, fire on board, to secure the batteries from problems of overheating. The 2 E/P pumps installed on board for Fire/Bildge services, each one sized to have a mass flow rate of 45 mc/h, installed with the possibility to operate simultaneously through manifold of at least DN80 can fill the compartment in a time lower than 10 mins, and this solution can reduce the possibility that, in case of fire in another compartment, temperature of the batteries rises.

The first objection that can usually arise considering the problem of contact between water and batteries, must consider the fact that the batteries packages installed are already cooled with water, insulating the single cells from the contact with water. The possibility of reaction between Lithium and water is then prevented also during the normal operation, and this is obvious otherwise also the possibility of damage of the compartment, according to the traditional stability parameters, could lead to a serious risk, in fact in case of collision the water could penetrate inside the battery compartment and cause serious problems.

The size of each of the 2-battery package is about 1000mm x 350mm x 350mm, in 2 blocks, modular to be easily dismounted in case of need. The battery compartment is obviously provided with the static ventilation system to prevent any storage of gas inside the compartment.

For this reason, the paper wants investigate the possibility of using a system like this, cooling the batteries, and the consequences on stability, to evaluate the opportunity to develop different methods to prevent the risk of explosion in case of fire on board. It is also important to underline the potential risk of overheating as consequence of fire on board, with a heat transmission from areas involved on fire to the battery compartment, also after the fire extinguished. The problem of cooling the batteries can then be underestimated even with the presence of heat insulation in the compartment.

The main difference arises when the stability is checked in damaged condition and in "Batteries compartment flooded" condition.

The study of naval hydrostatic explained, and is well known, that having a compartment "filled", totally or partially, is different from having the same compartment damaged, especially considering load and effects on GMT: these consequences oblige the naval architect to a new approach to the hull design for the damage stability. It is obvious, again, the need to insulate batteries from contact with water otherwise also the damage criteria, already applied and studied on ships will be useless.

The damaged stability criteria adopted accordingly to the European Union Rules the 2006/87/CE, 2006/137/CE, 2008/59/CE,2008/68/CE and 2008/87/CE, are extremely severe, imposing to verify the stability with all the passengers located on one side of the ship, starting from the higher bridge.

4.1. Other Limits Are

- Angle of equilibrium less than 10°
- Freeboard always more than 0,10 m
- Rah diagram area from angle of equilibrium and angle of flooding >= 0.0025 m/rad.

In order to better understand the consequences on stability if there is fire on board , and consequentially the flooding of the battery compartment is decided (as extreme measure to prevent overheating), the research performed the stability calculation, considering only the most severe condition of "Full load departure" with all the passengers boarded, crowding the Upper deck, in different situations:

- Intact stability, full load without and with Compartment "filled" at 98%
- Intact stability, full load with crowding of passengers on side (according to Rules), with and without the Battery compartment "filled" at 98%
- Damaged stability, full load, with and without the Compartment 5 filled at 98%, considering the damage of the compartments in the fore part of the ship, N. 4 and 6 , creating the most relevant trim by the bow for the ship. In this case is possible verify the reduction of GMT and freeboard.

The calculation has been executed starting from the "Stability booklet" of similar ships, trough a statistical analysis of the VCG and GMT values, in order to obtain a "real situation" describing the real consequences on stability.

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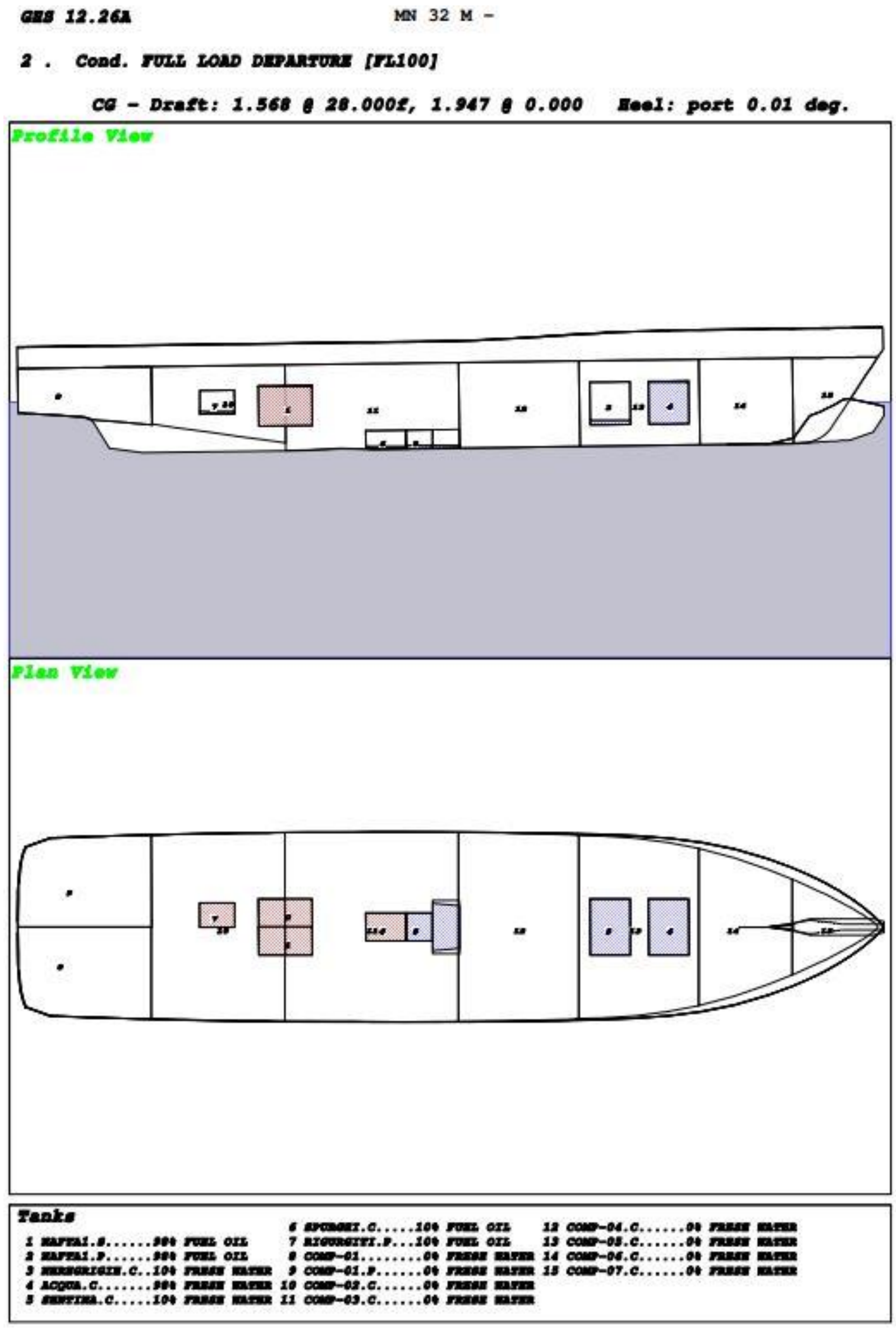

Figure 4.
Intact stability and compartimentation.

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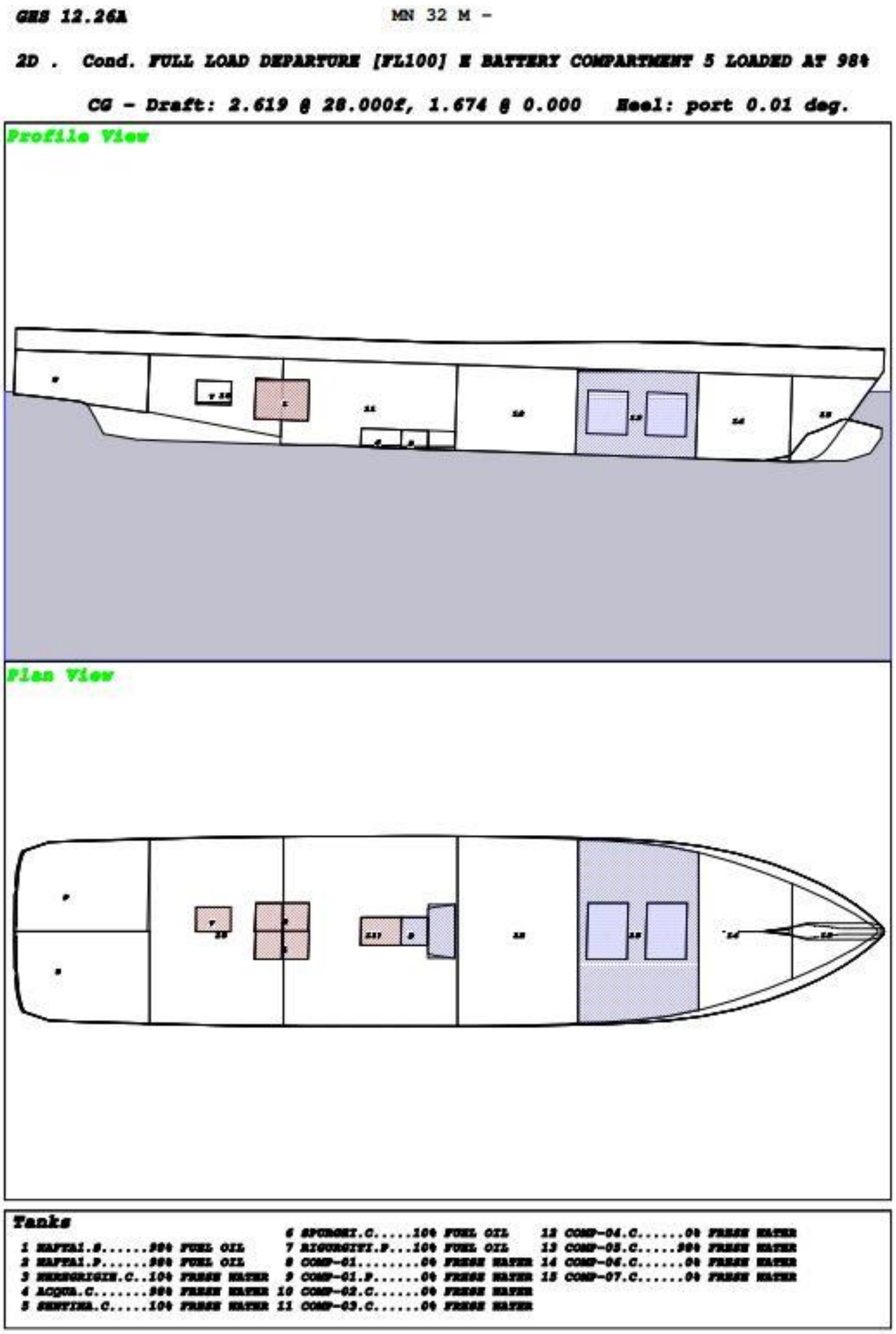

Figure 5.
Full load but with battery compartment filled at 98 % as for SOLAS recommendations.

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The results of calculations for Intact stability are summarized in the following Table 3

Table 3.
The tab shows the main parameters of stability according to the Rules of Inland water vessels.

	GMT (m)	**Rah**	**Area 0-FLD (m x rad)**	**θ_{FL}**	**Angle of heel**
Full load	1.12	0.37	0.14	32.2°	0°
F.load-Battery full water 98%	0.93	0.32	0.08 Limit 0.065	28.6°	0°
Full load pax on side	1.12	0.32	0.10	27°	4.1°
Full load pax on side Battery full water 98%	1.04	0.25	0.058 Limit 0.065	20°	3.91°

In case of wind and simultaneously crowding of passengers on a side (other criteria required by the Rules), the stability criteria are more at risk and need even more attention.

The tab. 3 results show a reduction of Intact stability, still matching the criteria for passengers in normal position, slightly under the limit of area of GZ curve, but with a significant warning to the future developments that should be carefully evaluated.

It is important to remind that this verification is not yet required by the Rules, it is a further investigation of what could happen assuming to use the flooding of battery compartment as a extreme measure to reduce temperature of batteries.

After the intact stability the calculations have been made, with reference to the condition of damage in Compartments 4, 6, and with the assumption that a fire is originating on board and the battery compartment "5" need to be filled with water to prevent the overheating of battery packs.

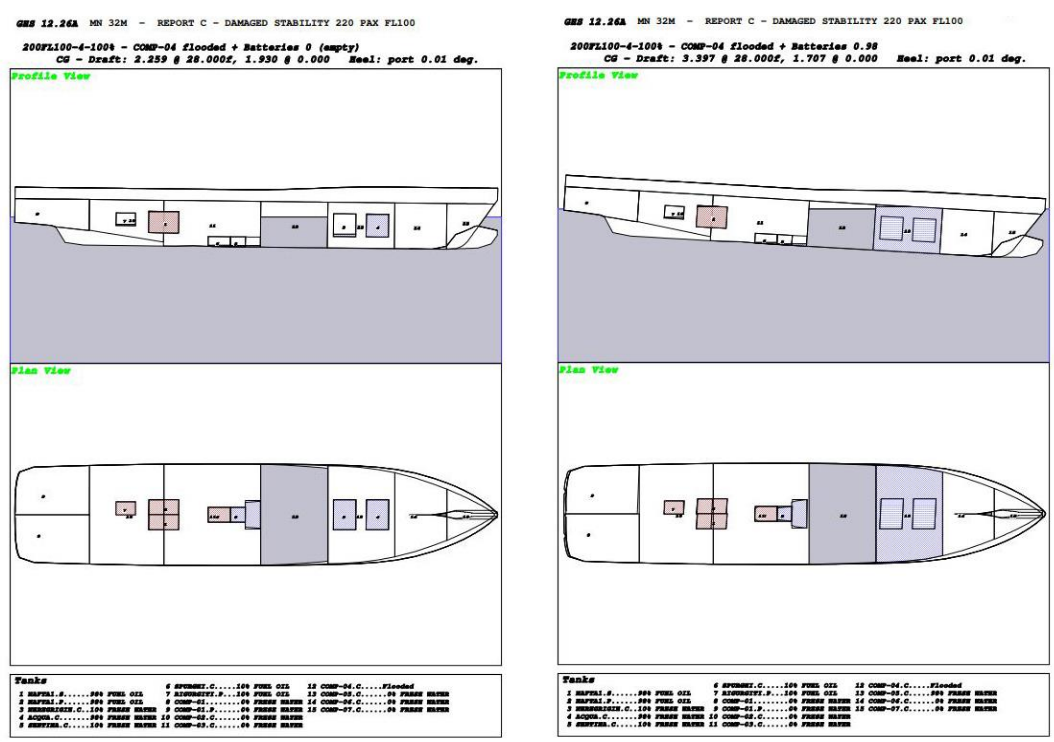

Figure 6.
Damage stability, compartment 4 and compartment 4 and battery compartment (5) filled.

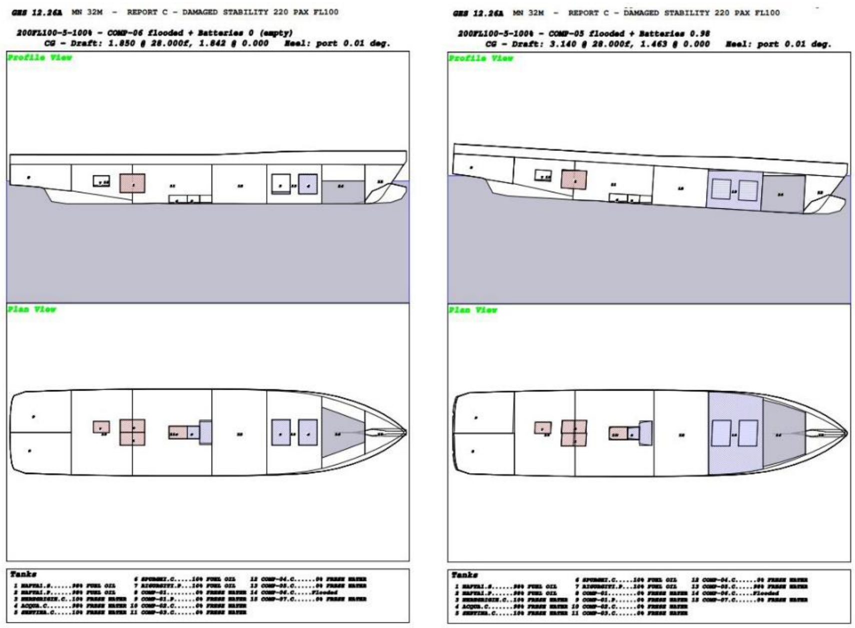

Figure 7.
Damage stability, compartment 6 and compartment 6 and battery compartment (5) filled.

The results of calculations for damage stability are summarized in the following Table 4

Table 4.
The tab shows the main parameters of stability according to the Rules of Inland water vessels.

	GMT (m)	Rah (m)	Area 0-FLD (m x rad)	θ_{FL}	Fb res (m)
Comp 4 Damaged	0.9	0.29	0.07	25°	0.91 (Bow)
Comp 4 Damaged + C5 batteries 98%	0.74	0.12	0	14°	-0.31 (Bow)
Comp.6 Damaged	1.02	0.32	0.13	27°	1.35 (Bow)
Comp.6 Damaged+ C5 batteries filled	0.98	0.20	0.0	21.5°	-0.05 (Bow)

As it is possible to see from the above results, the flooding of the batteries compartment, in order to prevent overheating of batteries, has a significant impact on the Stability parameters, especially in case of the damage of compartment N.4, the ship has GMT above the limit (GMT > 0.74 m) but doesn't respect anymore the Freeboard and Rah area criteria.

The results of these calculations, even considering that the calculation are not required by the rules but are a "what if" scenario, assuming a further developments of the Rules, considering the possibility to cool down the battery packs with water, require to be evaluated carefully.

In case the Rules requires the adoption of a two compartment damage stability criteria (as consequence of number of passengers), again the stability of the ferry needs a complete rethinking of the project with different values of stability parameters and different compartimentation as consequence of the additional weight in case of water in battery compartment. These new evaluations could have a deep impact on the project and design similarly to what happened in the previous re-evaluation of Rules for inland waters vessel with significant changes in design [18].

These results must be carefully evaluated in consideration of the limited displacement of the ship and the corresponding limited stabilizing reaction in case of further movement of passengers.

6. Conclusions

The paper studied possible solutions adopted on small passenger vessels equipped with LiB batteries to reduce the risk of explosion in case the batteries are exposed to the heat of a fire on board. One solution can be the modification of the bilge /firefighting system. The solution studied, makes possible fill the compartment in a reasonably short time (about 15 min) but shows also evidence of impact on stability. As a consequence of this solution the position of the compartment and his size and the possibility to adopt a "V" shape of hull in the position where the compartment is located, are important parameter in order to give the possibility to the 2 EE.PP. to provide a level of water inside the compartment high enough to basically cover and cool down a large part of batteries, also avoiding the need of embarking a large amount of water, with consequent good advantage on stability and residual freeboard. It also evidences the opportunity to install the batteries in a low position inside the hull.

But the paper underlines also the risk connected to the solutions studied in literature of extinguishing the fire in battery compartment or preventing an overheating by the above solution to flood the compartment of batteries using water, because the solutions used need to be accompanied by an evaluation of changes in stability.

Maritime industry, ship construction industry, chemical industry should focus on studying how to increase the level of safety, operating on both batteries and systems, considering also the possibility to develop and increase the installation of batteries based on different technologies, for example the sodium-ion batteries, with a better, safer, behaviour in case of exposition to the high temperatures.

The author's recommendation is, in presence of installation of large pack of batteries, to study means to prevent the risk of overheating in case of fire on board and to revise the stability criteria as consequence of the possibility to use compartment flooding as mean of cooling, of course as an extreme measure to adopt in case the fire is originating in a different compartment but is causing a serious rise of temperature in the battery compartment.

It is also important underline the problem of contact of water with the active elements contained in batteries, contact that can happen also by damage of the hull, adopting all the manufacturing requirements to increase the level of safety of batteries.

In case of use of water for fire extinguishment or cooling, also the problem of the post treatment of the water used will need to be considered to avoid pollution.

Finally, the papers demonstrate the need to study carefully the problem of firefighting when the propulsion system is based on large battery packs, possibly increasing the level of safety by the adoption or new systems or technologies.

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