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Artificial Intelligence Implementations Towards Shaping the Future of Digital World

DIGITALIZATION OF MARINE POWER SOURCES: FROM THEORY TO PRACTICE

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ABSTRACT

The maritime industry is undergoing a transformative shift driven by the twin imperatives of sustainability and operational efficiency. Hybrid power generation systems, combining renewable energy sources are emerging as a cornerstone of this evolution. These systems not only reduce greenhouse gas emissions but also optimize fuel consumption, aligning with stringent international regulations like the IMO's decarbonization targets. Simultaneously, digital transformation is revolutionizing maritime operations. Advanced technologies like the Internet of Things (IoT), big data analytics, and Artificial Intelligence (AI) enable real-time monitoring, predictive maintenance, and efficient energy management. Digital platforms enhance decision-making by providing actionable insights into fuel efficiency, route optimization, and system diagnostics, while also improving compliance with environmental standards. The convergence of hybrid power generation and digital technologies is paving the way for smarter, greener maritime operations. The synergy between clean energy and digitalization is not just an opportunity but a necessity for the maritime industry to remain resilient and competitive in a rapidly evolving global landscape. However, challenges such as high initial costs, cybersecurity risks, and interoperability with legacy systems must be addressed. Collaborative efforts among stakeholders, including shipowners, technology providers, and regulatory bodies, are critical to overcoming these barriers. This paper explores the role of hybrid power systems and digital transformation in achieving sustainable maritime operations, highlighting innovations, challenges, and future directions. A real case study involving these topics is also presented by the authors.

Keywords: IoT, Energy Management System, Machine Learning, Artificial Intelligence, Digital Transformation, Servitization

1. INTRODUCTION

The maritime field is one of the most important economic and strategic sectors of the European continent: as remarked by the European Maritime Safety Agency (EMSA), despite the temporal decreasing due to the COVID-19 pandemic, there is still the highest number of passengers carried by ships. Furthermore, three quarters of the international European trade is by sea as stated in [1]. These data give an idea about the strategic importance of the ships for the international market. For that reason, reaching the goals required by the Paris Agreement 2050 and by the ONU Agenda 2030 is crucial and needs to ensure the continuity in maintaining the competitiveness of one of the most strategic and profitable market of our continent.

In this context, the reduction of the emissions can be obtained not eliminating the traditional concept of the ship, starting from the traditional marine diesel engines, but improving it with a deep digitalization that allows an intelligent management of all the data coming from the asset.

In this way, information hidden inside the data and the trends can be extracted by AI algorithms. This information allows to understand the working status of the engine, and the operators can better manage the maintenance actions based on the predicted failure occurrence and knowing which components need to be replaced. Thus, an increasing of the safety of the ship operations is performed and the engine is protected from working in faulty conditions. It is an initial step for reducing the environmental impact of the maritime sector; in fact, an engine working in faulty conditions have emissions higher than 3% than one working in healthy status, as shown by Iraklis *et al.* [2]. This example highlights that the traditional and consolidated concepts need to be rethought. One of them is the maintenance paradigm.

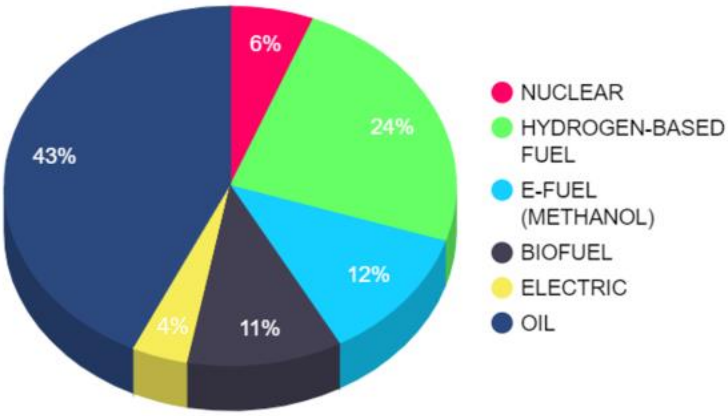
Until recent days, the maintenance has been performed in a preventive way, namely it is performed independently from the real status of the components, the time in which the maintenance action is required is planned in advance based on similar applications. This approach, widely used in the maritime sector is described by Cicek *et al.* [3], where a Failure Mode and Effect Analysis (FMEA) is applied on a marine engine.
Differently from that, a new maintenance concept has been proposed recently: the Predictive Maintenance. Although different are the names used for this kind of maintenance (Langone *et al.* [4] and Maione *et al.* [5] refer to it as Condition-Based Maintenance, Han *et al.* [6] refer to it as Prognostics and Health Management), the main concept is the same: using the constant monitoring of the asset, the failures occurrence can be predicted in advance.
In this case, the maintenance operations are planned only when strictly necessary, avoiding all the common drawbacks of a preventive maintenance approach: no-required maintenance operations and not useful idle time. This allows to increase the safety, both for passenger and transported goods and the usage of the ship is maximised.

Although the implementation cost of a predictive maintenance could be high (hiring expert technicians, implementation of technological systems to storage and process data, etc.), the saving of money consequently to the aforementioned advantages is clear.
The predictive maintenance is often applied with AI algorithms, namely Machine Learning (ML) and Deep Learning (DL) algorithms. Important examples, applied to diesel engines, are reported by Maione *et al.* [7] and Ceglie *et al.* [8]. In the first study the Long Short Term-Memory (LSTM) algorithm has been used for predicting the law decay of the monitored variables; in the second one an Artificial Neural Network (ANN) has been trained for predicting the expected sensors measurements to compare with the real one. These two examples give an overview of the importance to implement AI tools and can be easily extended to all potential on-board power sources.
A comprehensive overview about the deep digitalization that is occurring in the marine sector is proposed by Aslam *et al.* [9], where is remarked that this digitalization process is interesting all the aspects of the maritime sector, expanding the concept of "smart ship" to "smart ports".
The updating of the traditional concepts related to the ship, like the maintenance, is one of the useful ways to reach the strict requirements of the new challenges, but it cannot be the only one: performing a synergic and comprehensive collaboration searching and investigating new system for on-board power generation is necessary. For that reason, the investigation of alternative fuels, namely full-electric and hybrid ships, is necessary for the future development of one of most traditional industrial sectors like the maritime one.
It is worth noting that the two proposed solutions, namely the digitalization and the investigation of new power sources, are not separate ways but a unique powerful approach for a deep and necessary improvement of the maritime sector. Raspone *et al.* [10] gives an optimal overview of the integration of ML algorithms with the new power sources, like the hydrogen fuel cells.

2. OVERVIEW OF MARINE POWER GENERATION SOURCES

The energy sources used to propeller a ship and satisfy the on-board needs can be divided into three groups: traditional, renewable and hybrid. The traditional one is the well-known Internal Combustion Energy (ICE), namely the traditional diesel engines widely used to its efficiency, reliability and its capacity of generating the high power required by a ship. On the contrary, as renewable energy sources are considered not only the solar and windy ones, but also the systems supplied with new kind of fuels produced by renewable energies such as ammonia, as shown by Gallucci et al. [11] and hydrogen, as explained by Haxhiu et al. [12]. Finally, the hybrid ones, as remarked by Akorede et al. [13], are the technologies that combine more than one energy sources.

Although the three energy sources are often analysed differently, it is worth noting that they need to be seen as an ensemble. Only in this way it is possible to reach the goals required by the Paris Agreement 2050 and the ONU Agenda 2030. As stated by the Det Norske Veritas (DNV) within the Energy Transition Outlook 2024 et al. [14], where it is highlighted that the world seaborne trade will increase by the 2050, to meet this growing demand a huge integration of different energy sources is necessary. In the same report, a forecasting of the energy demand is performed too, as shown in Figure 1. It is remarked that the oil demand will decrease but will not disappear, while other power sources like the natural gas, the e-fuels, the electricity, the ammonia and bioenergy will have a big increment. These data give an overview of the importance of integrate different energy sources



without a drastic elimination of the traditional one, still necessary both for preserving the economic importance of the maritime marked and because only a collaborative effort can reach the desirable environmental results.

Figure 1 - Maritime Fuel Mix Forecast 2050 (from [14])

2.1. Traditional Power Sources

A traditional power sources is an energy sources traditionally used in power generation. Examples are the oil and the petroleum. In this context, a traditional marine diesel engine is a big asset that can be divided into different subsystems in order to analyse in an easy way its working behaviour. This approach has been followed by Kougiatsos *et al.* [15] and Ayah *et al.* [16]. The subsystem identification is made based on the different operations that are necessary for guarantee the optimal working condition of a diesel engine. In the current study authors propose to divide it into: Air and Gas Subsystem, Lube Circuit, Cooling Circuits and Fuel Circuit.

As remarked in the introduction, although the marine diesel engine is classified as *traditional* power sources, it is worth noting that the deep digitalization of the maritime sector force to re-think also the traditional propulsive plants. In fact, to perform an intelligent management of the engine, the sensors need to be installed in sensitive and crucial points, where meaningful variables can be monitored. In this way, the acquired data will be deeper analysed by AI algorithms to handle high dimensional and multivariate data and extract hidden relationships among data collected from complex and dynamic environments.
It is worth nothing that an intelligent management of a traditional plant like the diesel engine is potentially easier than a one performed on a new power source. In fact, the already existing knowledge allows to better understand the crucial parameters that are important to monitor and

analyse. On the other hand, the fact that diesel engines are on already existing ships makes more difficult the new sensor installations and the implementation of intelligent monitoring systems.

2.2. Renewable and Hybrid Power Systems

As remarked before the hybrid energy sources are all the solutions that integrate different kind of power sources: often the renewable ones are used as support for the traditional one. Herein different examples are reported for giving an idea about the applications of these power sources in the maritime sector.

In Yuan *et al.* [17] a general analysis of the hybrid multi-energy naval application is made. Authors highlights that the hybrid systems, following a careful modelling phase, can effectively decrease the energy ship consumption. One of the main results shown in the study is the fact that the multi-energy hybrid systems are strictly correlated with the type of application. This makes difficult a theoretical and general approach.

In Melideo *et al.* [18] an important study about the retrofitting activity on an already existing ferry ship is proposed. More in details, it is a preliminary study for a hybrid retrofit with fuel-cell. Three different scenarios have been analysed: (a) Total replacement of the engine, (b) Replacement of auxiliaries only and (c) Auxiliaries replace with fuel-cell and on-board load supplied by auxiliary engines. In this case no emissions in port are performed.

In Inal *et al.* [19], similarly to Yuan *et al.* [17], a comprehensive overview of current hybrid energy sources in the maritime sector is given. More in details, in the study is remarked that the Energy Storage Systems (ESSs) have the highest efficiency. It is because the ESSs compensate imbalances and load variations that cause the power generator to work in not-optimal conditions. Moreover, the supercapacitors provide higher power than batteries, namely they better manage the fluctuation of load demand. In the study also the methods for managing the energy are analysed: Rule-Based and Optimized Control Strategy (in this case AI technique can be applied). Finally, considerations on the most suitable configuration based on the type of ship are performed.

In Saponaro *et al.* [20], a preliminary design of a fuel-cell hybrid power system is shown. Herein, a ferry application is taken under consideration for analysing the study of the stack degradation of the fuel cell system through a digital twin.

In Wang *et al.* [21] an offshore support vessel study is presented. Herein a propulsive plant obtained combining ICE, batteries and fuel cell is proposed. Different operational load profiles have been considered to estimate the hydrogen consumption. Three scenarios have been simulated to obtain emission reduction of the 10%, 50% and 100%. For a reduction of the 10% the fuel cells do not give any contribution, only the batteries are necessary. For a 100% emissions reduction the fuel cells are sized for a power that is the mean of the power load profile. In this case the batteries compensate the peaks.

All the presented studies give an overview of the activity that is currently performed for improving the environmental impact of one of the most important and strategic sectors in the world. It is a huge challenge; in fact, has reported by the European Union *et al.* [22], the maritime transports contribute for the 3% of the global emissions related to the human activities. Although this number can be seen as a low value, it contributes to the global environmental impact and to its huge consequences. In fact, all the transport sectors produce 8.7 gigatonnes of emissions. Furthermore, to cut the 42% of the emissions (it means that we need to reduce the emission to 22 gigatonnes per year)) and contain the temperature increasing low than 1.5°C, a synergic contribute of all the industrial fields is necessary, from the most to the least polluting. To act in a fast way is important combine the research of new fuel and propulsion technologies, with the gradual integration of them in the already existing power energy source. For that reason, the hybrid solution play an important role.

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3. ROLE OF DIGITIALIZATION IN MARITIME SECTOR

Digital transformation (DT) is an evolving process that involves using capabilities and digital technology to create or modify business processes, operational processes, and customer experiences, leading to new value creation. In other words, using a combination of digital innovations that change the structure, values, processes, positions, or ecosystems within organizations and the environment outside of organizations is what results in digital transformation, as stated by Hinings *et al.* [23]. In general, DT is currently an important trend that penetrates many industrial and societal domain.
Therefore, even the maritime sector can't be spared from this phenomenon. In fact, the maritime industry is experiencing a fast-paced transition towards digitalization and advanced automation. To enhance operational efficiency and increase competitiveness, digital technologies and solutions are being employed. The implementation is intended to encourage the industry to decarbonize and achieve zero emissions from international shipping by mid-century, as shown by IRENA *et al.* [24].

In Imam *et al.* [25], it is investigated and shown that DT could have the potential to significantly enhance the performance and resilience of maritime supply chains. An important role in this transformation flow is played by the cutting-edge digital technologies such as Internet of Things (IoT), AI and Blockchain Technology (BCT), as well analyzed by Jovic *et al.* [26]. The latter, due to its excellent characteristics, is slowly being implemented to address the problem of information interaction in the global supply chain. Collaborative commerce can be facilitated by blockchain, and licensed parties can access trusted data in real-time. Therefore, it's easy to understand how BCT can enhance procedures in the global maritime transportation network through digitalizing and helping to keep real-time track of the status of cargos and improving global visibility of marine traffics and exchanges.
Regarding IoT and AI in maritime sector, further the authors address these topics with more detail.
It's important to highlight even that DT brings with it a refashioning of the business models of the maritime stakeholders, toward the model of the so-called *servitization* approach.

Servitization is a paradigm developed around technologies that use data to extract new knowledge and developing enhanced functionalities for final customers. Generally, it describes a strategic transformation for which enterprises shift their focus from selling products to offering a combination of products and services. This is deepen studied by Formisano *et al.* [27].
The authors within this paper are focusing on the always increasing hybrid power generation systems installed on-board of ships and the digital transformation surrounding them, but considerations could be extended to all subsystems involved in offshore environments.

3.1. On-board IoT architecture

Connected devices and the growing demand for data-driven insights have led to the explosion of the Internet of Things (IoT) market in recent years. The industrial and transport and logistic (T&L) sector's use of connected devices to optimize supply chain operations, improve efficiency, and reduce costs is one of the key drivers of this growth. The trend is predicted to persist as more and more businesses embrace the power of IoT to transform their operations and achieve a competitive advantage in their respective industries, as shown by a report of the platform IoT-Analytics *et al.* [28].
A ship is a complex system where a huge amount of data is generated from various sources (on-board subsystems) and formats, therefore the IoT paradigm well fits with the needs of the use-case, to support the maritime DT.
The macro-subsystem of the ship's power-sources is the most important on-board equipment; thus, it is crucial focusing on it for developing innovative strategies to enhance capabilities and general performances.

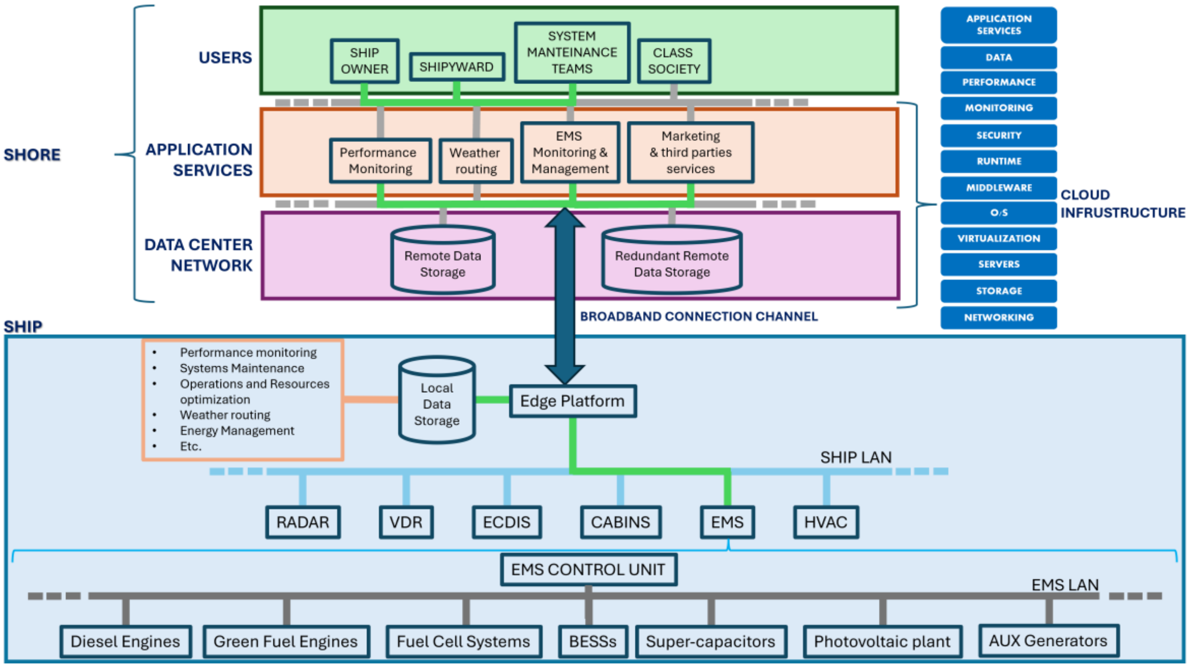

Figure 2 - High level IoT network for on-board applications

Figure 2 shows a high-level IoT blocks-architecture proposed here for ship remote monitoring and management, highlighting the Energy Management System (EMS) details. The whole layered architecture is thought to be highly scalable and supports different kinds of ships, in terms of operative missions (cargo, human transportation, military, etc.) and size. The ship side consists of the Edge Platform (EP), or rather a centralized system aimed at providing on-board services to the crew. The EP oversees interfacing with all sub-entity Automation, Control and Supervision (ACS) systems, collecting monitoring data from them and sending back control signals. The acquired data are stored in a local data storage environment. On top of this, the EP implements local advanced and fundamental services, in terms of overall safety for navigation. EP then manages the connection with the remote Cloud Infrastructure (CI).

The whole CI is designed for storing data in proper databases, based on the type of information, and having a certain number of containers where functional applications are implemented.
The *Application Services* layer is where the servitization paradigm occurs and IoT combines with ML and AI. Thanks to lower layers and technologies, data are collected, stored and processed (transformed for further usage), then multiple applications run and offers services to final users based on specific roles, such as real-time monitoring, behavior predictions, system settings, ticketing management, report generation, and so on.
Among all the services, those referred to EMS play a key role due to the high reliability required to it and the always increasing complexity due to the integration of different power sources. As shown, in the future such a system like this must guarantee the management of multiple power sources, properly orchestrated to work together on the same power bus and being compatible with different power demands.
The interaction between the single power sources and the power consumers (on-board loads) is guaranteed by a central control unit. The latter communicate, via standardized communication protocol and hard-wired lines, with each power source's ACS system and take actions based on implemented control logics.

3.2. Opportunities and Challenges

Basing the Digital Transformation process of the future ships on the adoption of the IoT paradigm could have lots of benefits as understood up to now: *increased operational efficiency* (reduced fuel

consumption and optimized equipment usage), *enhanced safety* (early detection of failures minimizes risks to crew and cargo), *cost savings* (predictive maintenance reduces downtime and repair costs), *environmental compliance* (continuous monitoring of emissions ensures adherence to IMO regulations), *data-driven decisions* (real-time insights enable operators to make informed decisions). These are just some of the main benefits coming from the adoption of IoT in maritime. However, the process is not free of potential issues and need to be carefully, as further detailed.
Security and privacy are extremely critical points to be analysed, since the global data transmission perimeter changes when IoT technologies are integrated on board. This means, data are exposed to external world and need to defence information. Vulnerability to cyberattacks must be opposed with properly strategies, adopting the general approach of the *zero-trust.* Important is also the fact that multiple users will access to data, then the management of the personal information must be handled with compliance to reference standards (e.g., EU Regulation 2016/679, General Data Protection Regulation - GDPR).

Integration complexity is one issue referred to legacy systems that can't integrate seamlessly with IoT architecture. In Rodseth et al. [29], a very deep study of the main ICT (Information and Communication Technologies) architectures and standards to be adopted on ship is provided.
Connectivity Issues need to be analysed too. These arise due to the unique challenges posed by the vast, remote, and often harsh environments of the open seas. These challenges impact the ability to establish and maintain reliable communication and data transfer. *Coverage limitations*, *bandwidth constraints* (increasing use of advanced systems, onboard sensors, and crew welfare needs, e.g., internet for personal use, could strain available bandwidth), *interference*s (storms, high waves, and extreme weather conditions can disrupt radio signals or onboard communication equipment, as well as physical barriers, e.g., vessel or surrounding terrain, can block the propagation) and *latency* are aspects within the matter of connectivity that must be treated, especially when the final customer services are outsources from the ship, as the digital transformation is showing.

High initial costs could be another topic for slowing down the adoption of IoT paradigm in maritime, despite the general long-term operational benefits. Usage of specialized hardware and infrastructure (as rugged modules, more complex and secure ICT architecture), retrofitting activities for integrating with legacy systems, upgrading of connection infrastructures, workforce training (skill developments and new specialized personnel for implementation and maintenance of systems) and regulatory compliance aspects, play an important role in initial impact evaluation. Some strategy to mitigate the high initial costs could be to act a scalable implementation, therefore starting with pilot projects to prove Return-of-Investment (ROI) before fleet-wide deployment or extend to other customers. On cloud side, opt for subscription-based cloud platforms can help to lower software development and maintenance costs, with possibility to scale storage and computational resources based on existing requests.

3.3. Data Analytics and Predictive Maintenance

As remarked in the previous sections, the maritime maintenance strategies are under a deep improvement. If until recently they were performed with a time-based approach, namely they were scheduled on fixed time-intervals, now the main philosophy consists of predicting the failure time occurrence. It is worth noting that one of the main goals of the new maintenance paradigm is to build a system that can support the ship operators in managing in a better way the main assets, such as an engine. For that reason, the maintenance digitalization has the goal to realize a digital comparative system that gives information about the expected working conditions of the monitored machinery, provides suggestions about the corrective actions to perform, or predictions about the type and the time of the failure occurrence. An example is presented by Gharib *et al.* [30] that developed an Expert System for a four-stroke marine diesel engine. Herein, once the most meaningful diagnostic parameters have been chosen, the system has been built in accordance with experimental results and experts' knowledge. In this way, the obtained system provides diagnostic support depending on the expected working conditions of the engine. In general, building a suitable diagnostic tool follows different approaches, depending on the chosen models: *Knowledge-Based* (as reference, Ventikos *et al.* [31]), *Model-Based* (as reference, Rubio *et al.* [32]) and *Data-Driven Models* (as references, Maione *et al.* [7] and Ceglie *et al.* [8]).

4. CASE STUDY FOR DIGITAL TRANSFORMATION OF EMS

This section gives an overview of a prototype system developed in collaboration with Isotta Fraschini Motori (see https://www.isottafraschini.it/) for monitoring and management of remote power sources, based on the paradigm of IoT and driven by the digital transformation desire in the maritime. At this phase the whole system is based on the architecture shown in Figure 3 and is being tested in a land plant in a controlled environment. The prototype is thought for being proposed as cloud and on-premises solutions based on customer needs. This means that the high-level services can be offered directly on-board of the ship for a local usage or moved remotely according to what shown in Figure 2. The system is designed to centralize the most important information regarding a hybrid power generation plant, collected and managed by the EMS, within a single platform. The overall capabilities are the right and optimized usage of multiple power sources based on power demand, operative scenarios and pre-defined operative working modes. The latter are mainly based on tree approach: rule-based, optimization-based and learning-based, considering external dependencies such as weather conditions, fuel costs, etc.

The control capabilities are integrated with powerful capabilities in terms of diagnostic and prediction, based on a strategy combining knowledge-based and data-driven approach. Its creation has been developed around the diesel engines, then extended to other type of assets. General approach requires initially classifying the most common failures of the marine power sources. To do that, several experts technicians of the company IFM have been involved into the study. Then, based on the current sensor measurements the diagnostic tool uses the knowledge acquired from the company expertise for evaluating the rea-time status of the engine. A DL algorithm makes predictions on the future sensors measurements trends. Among the different DL algorithms, the LSTM has been chosen. It is an improvement of the traditional Recurrent Neural Networks (RNNs) that allows to recognize and predict time-based patters. Based on the predictions made by the LSTM, the diagnostic tool, similarly on what has been done in the second point, evaluates the future status of the engine.

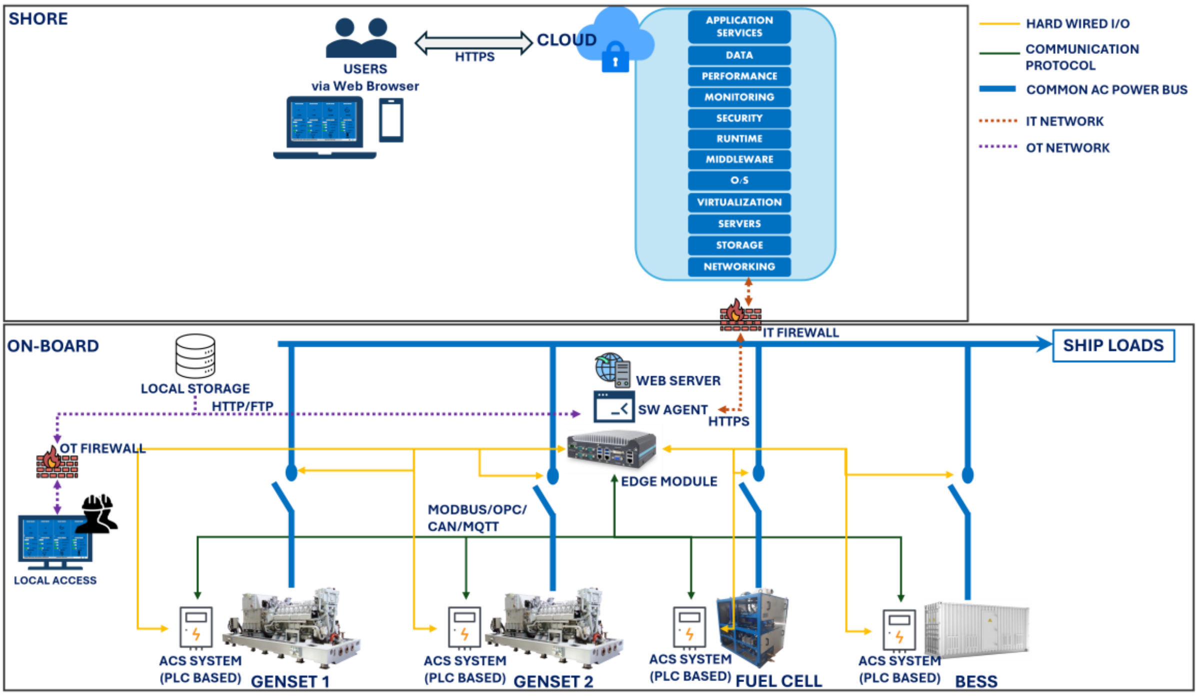

Figure 3 - Hybrid power generation system prototype

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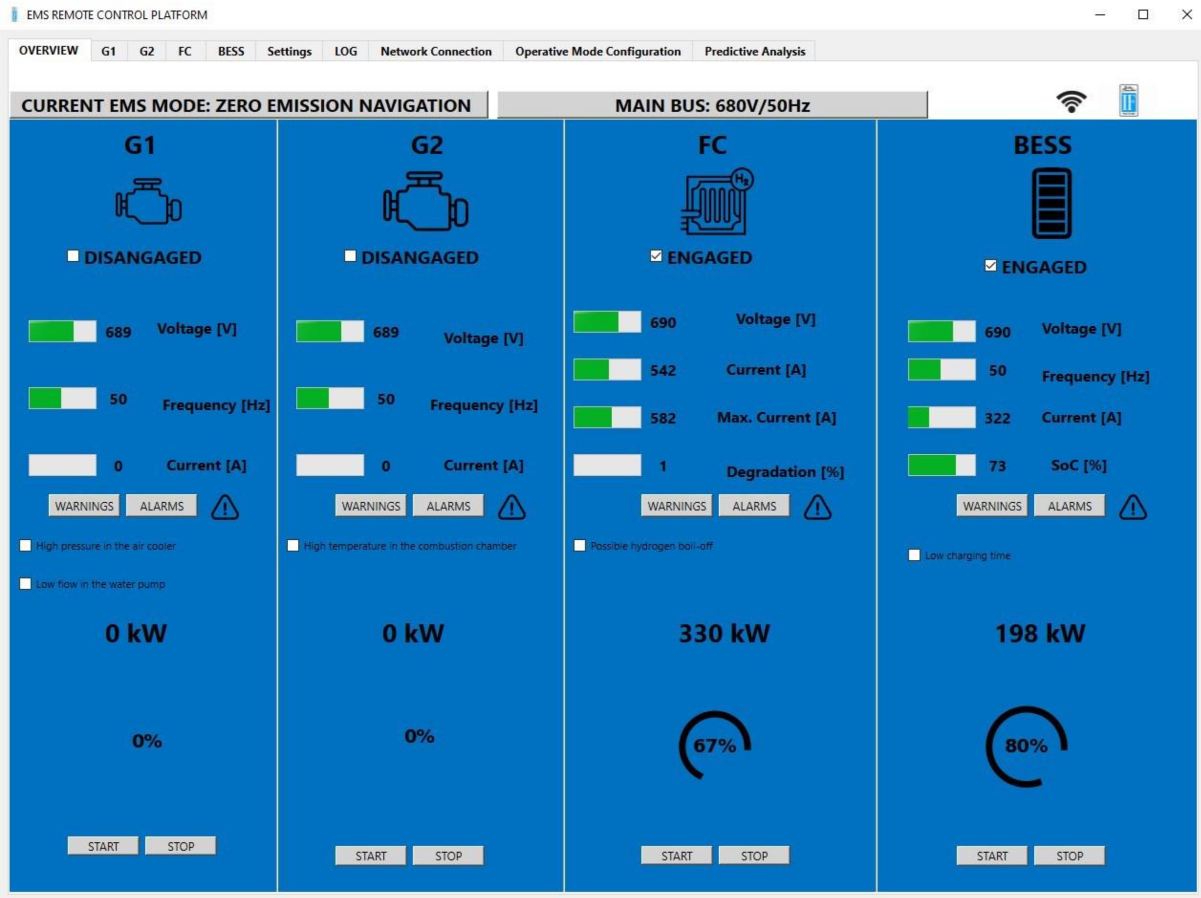

Figure 4 - Summary view of the EMS platform

In Figure 4 and Figure 5 two main views of the remote and management platform of the hybrid power sources system are presented. In particular, the example refers to an EMS for on-board applications, equipped with four power sources: two diesel engines, one Fuel Cell (FC) system and one Battery Energy Storage System (BESS). For all, the main power parameters are illustrated, the engaged/disengaged status and the power contribution to the system. As already said above, the EMS works with pre-defined operating mode (in Figure 4 the *zero-emission navigation* requires that gensets are switched off, with a constrain on the total power capacity). The warning and alarms section lists a high-level information derived from the processing of row data, helping the user to immediately understand a potential failure. On the top of the prototype dashboard, the operators have the possibility to choose among different tabs where detailed views of each power source and of the overall system are illustrated. A dedicated view to diagnosis and predicted behaviour is reported in Figure 5. Herein, the users can check the future engine health status, based on the selection of available predicted parameters. At the bottom, a general overview of the predictions has been made comparing the means of the predicted trends and the ones expected in case of engine working in healthy condition. Again, a fast-use information on period of occurrence and type of event is provided to the user.

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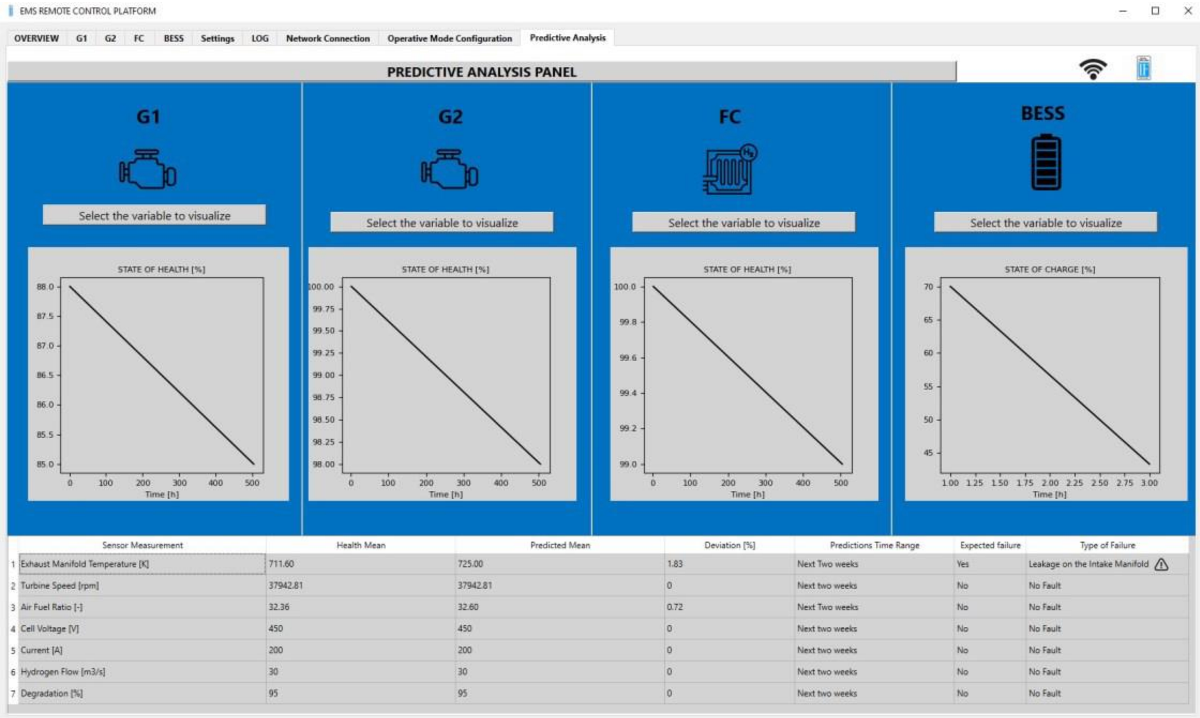

Figure 5 - Predictive analysis view of the EMS platform

5. CONCLUSIONS

The current study addresses two different challenges that are involving the maritime sector into a deep changing: on one hand, the digital transformation that is happening in all industrial sectors is opening the door to a big revolution also in the maritime sector; on the other hand, authors analyse how the on-board power generation is being moved to greener and efficient hybrid architectures, considering innovative power sources. More in details, the attention is putted on the monitoring technologies for hybrid marine power sources, highlighting advantages and challenges. Further, the authors propose a real case study where the IoT paradigm helps to enhance the capability of an Energy Management System orientating the whole architecture to the servitization approach. In this way, operators and involved users, with a synergic cooperation with AI tool and advanced user-interface, can easily and better manage the on-board power plant, reducing or avoiding faulty working conditions and increasing the safety of the ship, the transported goods and the passengers.

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