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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

AN OPEN SOURCE TOOL FOR EMISSION AND ENERGY ANALYSIS OF A GENERIC SHIP*

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ABSTRACT

Ships embodying a wide range of energy carrier conversion, end-use technologies and emissions, can be considered as a whole energy system and require focused analysis to provide guidance and foresight for naval engineers, ship operators and fleet managers. Considering the emerging technologies in marine industry and the new regulations promulgated by the local or worldwide authorities, benefiting the superpowers of computing technologies became vital in order to let the stakeholders keep their profits up while fulfilling the regulations and restrictions. Since optimizing a system is the focus of all kinds of engineering, software tools aiming to provide guidance for the decision makers have been widely used for the last decades. This study anticipates to bring a comprehensive and open ended software tool solution for the stakeholders and the researchers of the shipping industry and to be the first step for a sophisticated open source software tool which will shape with the help of future researchers.

Keywords: *Ship Energy System, Data Science, Open Source, Python, Energy Analysis.*

AÇIK KAYNAK KODLU GEMİ ENERJİ SİSTEM VE EMİSYON ANALİZİ ARACI

ÖZ

Gemiler sahip oldukları geniş kapsamlı enerji taşıyıcıları, dönüşüm teknolojileri, son kullanıcı teknolojileri ve gaz salınımları ile kendine has enerji sistemleridir. Bu nedenle gemi enerji sistemlerinin özel olarak ele alınıp incelenmeleri, gemi operatörlerine, filo yöneticilerine, gemi makina ve inşaatı mühendislerine ve diğer tüm gemicilik sektörü paydaşlarına rehberlik sağlaması açısından önem taşımaktadır. Gelişmekte olan denizcilik teknolojilerini ve otoritelerce yayımlanan yeni düzenlemeleri göz önünde bulundururken bilgisayar teknolojilerinin sunduğu güçlerden faydalanmak, sektör paydaşlarının karlılıklarını artırırken aynı zamanda yeni yönetmeliklere ve kısıtlamalara adaptasyon açısından önem arz etmektedir. Tüm mühendislik alanlarının ortak paydasının optimizasyon olması sebebiyle, yazılım araçlarının kullanımı son yıllarda çok yaygınlaşmıştır. Bu çalışmada, gemilerdeki enerji verimliliği ve emisyon konusunda, halihazırdaki düzenlemeleri göz önüne alarak, esnek, özgün ve yerli bir enerji analiz aracı oluşturulması hedeflenmiştir. Tasarlanan bu yazılımı bilgisayar teknolojilerindeki ve gemicilik endüstrisindeki süregelen değişimlere karşı esnek ve adapte edilir kılmak amacıyla açık kaynak kodlu programlama dili kullanılmıştır. Böylelikle aracın gelecekteki çalışmalarda kullanılması ve geliştirilebilmesi açısından da fayda sağlanacağı düşünülmüş ve bu aracın, mühendislerin ve diğer sektör paydaşlarının istifade edebileceği daha gelişmiş ve kapsamlı bir aracın ilk adımı olması hedeflenmiştir.

Anahtar Kelimeler: *Gemi Enerji Sistemleri, Veri Bilimi, Açık Kaynak, Python, Enerji Analizi.*

1. INTRODUCTION

Since shipping stands as one of the main elements of the international trade and the transport sector that would not be unfair to claim that shipping sector represent a substantial portion of both environmental pollution and the economy cakes. Concerning the contribution of the shipping transport sector to the global gas emissions, operations and the technology used within the sector have been widely put under scope by engineers, environmental scientists and even by the economists. Although it requires scientific researches and some time to confirm, couple of reports have been emerged claiming that the air pollution levels are decreased throughout the world's busiest cities due to the COVID-19 lock down. If these reports get approved by scientific researches, they will also highlight again the contribution of the transport and shipping sectors to worldwide air pollution. On the other hand, most of the scientific researches so far on this field claim that the demand for shipping will keep rising for the near future and needs to be contemplated in terms of efficiency and its contribution to environmental pollution. In this regard with its 167 main and 3 associated member countries, International Maritime Organization (IMO), an agency of United Nations has been working on this rising issue for the last decades and already promulgated some regulations with regards to the energy efficiency of the ships and the ship born gas emissions which means a challenging and a long path of adaptation awaits all the stakeholders of the shipping sector. Also considering the other parallel regulations put into force by other authorities and some governments, actors of shipping sector varying from ship designers and ship builders to the operators on board should immediately take action and stay vigilant to survive through the rapidly changing circumstances.

In this context while demand for the shipping sector rises every other year emissions are needed to be reduced in order to comply with the stringent measures taken by the authorities. Recent researches and the uncertain circumstances posed worldwide by the latest pandemic especially for the international transport sector will soon fire up new questions to be answered and possible solutions to these questions will tend to bring "new changes" for the sector as well as the World goes back to "new normal".

Since science and engineering are always resilient, we would not be disappointed even if we disregard the latest circumstances we are facing throughout the world and keep focusing on optimizing our current systems. So that we can focus on the latest issues we have before the pandemic, keeping in mind that for sure we will see some adverse effects or maybe some new ideas helping engineers to cope with all these issues after the World totally gets through this pandemic.

Ships also embodying a wide range of energy carriers, conversion/enduse technologies and emissions, can be considered as a whole energy system and require focused analyses to provide guidance and foresight for naval engineers, ship operators, fleet managers and other relevant stakeholders throughout the shipping industry. Considering the emerging technologies in marine industry and the new regulations promulgated by the local or worldwide authorities, benefiting the super powers of computing technologies became vital in order to let the stakeholders keep their profits up while fulfilling the regulations and restrictions. Since optimizing a system is the main focus of all kinds of engineering, software tools aiming to provide guidance for the engineers and decision makers have been widely used for the last decades. But as the amount of the data produced and collected by the shipping industry raises, analysing tools require being resilient and adaptable.

This study initially aims to define the current requirements and the regulations with regards to the energy efficiency and the emission control of ships and develop a comprehensive and resilient energy analysis tool solution for ships. Open source and specifically Python programming language has been chosen in order to keep the tool adaptable and resilient due to continuous developments in all the computer science, engineering and the shipping industry. Building the tool using open source coding considered beneficial as it will also give researchers and programmers the opportunity to use and improve the tool for future studies. Considering the wide range of Python libraries available especially on data science, aforementioned tool can be integrated with new modules such as the ones able to detect anomalies, find out possible reasons and provide recommendations in order to eliminate the factor affecting the energy system of a ship. The tool can also be enhanced with modules enabling the decision maker to compare two or more scenarios on a given ship.

Considering a ship as a single energy system could end up with incorrect results and bearing in mind that our energy system (ship) also interacts with outer energy systems such as sea and atmosphere would let the decision makers achieve more stable and accurate solutions. If we go into details, a ship operating in the North Sea has to interact with a sea temperature around 13°C in May while another ship operating in the Red Sea interacts with a sea temperature around 31°C and some more different atmospheric circumstances. Since a ship's main energy conversion technology is using internal combustion engines which transform chemical energy heavily relying on external conditions such as intake air temperature and coolant water temperature, this situational variation would lead a substantial difference between aforementioned two ships' energy systems and data science provides a great opportunity to overcome these kinds of differing circumstances. In this regard, this study anticipates to raise awareness on the issues of the sector related to the energy efficiency and emissions of ships, bring a comprehensive and open ended solution for the stakeholders and the researchers of the shipping industry and touch the base for a sophisticated open source software tool which will shape with the help of future researchers.

1.1. Aim and Research Questions

The aim of this study is to;

- Review the latest International Maritime Organization (IMO) regulations with regards to energy efficiency of ships and emissions caused by shipping industry to raise more awareness,
- Review what kind of preparations on-going by the stake holders including engineers, shipping companies, organisations and governments to comply with regulations,
- Focus on developing an open-source software tool which is suitable for further improvements.

Questions to be answered are;

- What type of data about the performance of the ship should be gathered to build a reference energy system of a ship?
- Considering the resilience of open source programming what kind of improvements could be achieved following the completion of reference energy system?

1.2. Review of the Latest International Maritime Organization (IMO) Regulations on Ships' Energy Efficiency and Emissions

At present, maritime shipping represents 80-90% of international trade. With global Gross Domestic Product (GDP) expected to grow 3.6% per year between 2019 and 2024, global trade volume is also expected to grow at a similar annual rate i.e. 3.8% over the next five years. Therefore, if no action is taken promptly, demand for marine fossil fuels will continue to grow steadily.

Considering the European Commission Joint Research Centre Emissions Database for Global Atmospheric Research (JRC-EDGAR) 2018 report relying on the data from IMO, shipping sector was also responsible for an average of 2.8%3 of all annual GHGs on a CO_2-equivalent basis, between 2007 and 2012. Between 2000 and 2017, CO_2 emissions associated with the shipping sector increased at an average annual growth rate of 1.87%. In 2017, the shipping sector was responsible for 677.25 Mt of CO_2 emissions (IRENA, 2019)

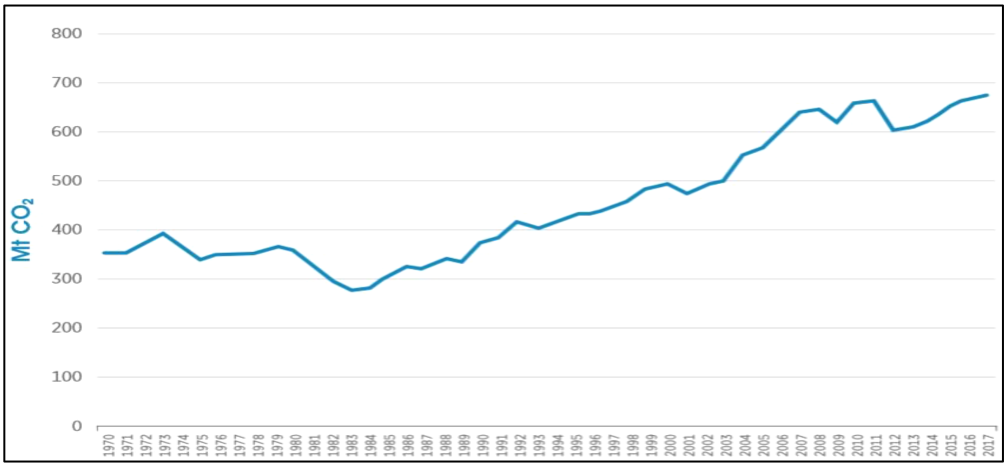

Figure 1. Ship born CO_2 emissions based on 1970-2017 JRC-EDGAR 2018 data (IRENA, 2019).

International Maritime Organisation (IMO) is an agency of United Nations (UN) specialised on maritime safety and established in 1958. IMO currently has 174 member countries and 3 associate members. After promulgating the International Convention for the Prevention of Pollution from Ships -as known as MARPOL 73/78- in 1973, a new annex named as the Regulations for the Prevention of Air Pollution from Ships (Annex VI) amended to the convention which seeks to minimize airborne emissions from ships (SO_x, NO_x, and other pollutants) and their contribution to local and global air pollution and environmental problems. Annex VI entered into force on 19 May 2005 and a revised Annex VI with significantly increased the emission limits was adopted in October 2008 which entered into force on 1 July 2010. IMO also adopted mandatory technical and operational energy efficiency measures which are expected to significantly reduce the amount of CO_2 emissions from international shipping. These mandatory measures (Energy Efficiency Design Index and Ship Energy Efficiency Management Plan) entered into force on 1st January 2013. (International Maritime Organization, n.d.)

Ship Energy Efficiency Management Plan (SEEMP) utilizes Energy Efficiency Operational Index (EEOI) as a monitoring tool and aims to provide guidance to the engineers and ship operators regarding the energy efficiency of the ships.

In addition to the aforementioned measures IMO has also promulgated the pollutant limits such as NO_x, SO_x and Green House Gases (GHG) globally and specific to some pre-defined Emission Control Areas (ECA).
In this regard some governments and authorities have already started to focus on implementations and researches to be able to comply with these regulations.

In 2015, European Parliament has published a directive on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport (European Parliament, 2015). The regulation requires ships above 5 000 gross tonnage (GT) to report their annual fuel consumption and associated CO_2 emitted during the voyages. Later in 2019 European Federation for Transport and Environment published a report aiming to translate the raw emissions and ship performance data collected from the EU shipping with regards to the European Parliament directive into policy relevant and relatable to general public knowledge (Transport and Environment, 2019). The study concluded that there is a large performance gap between ship design standards and real-world maritime operations considering EEDI and EEOI values. This study also declares the energy efficiency of fleets by giving company names out and ranking them.

Although these efforts does not seem to bring the work forward from where IMO has brought, one can say that these kind of reports would for sure motivate shipping companies to compete with the others by reducing the emissions and raising the energy efficiency of their fleets. Concerning the preparations and additional measures taken by the actors other than IMO and EU, a policy paper named ‘Maritime 2050’, published by United Kingdom (UK) Department for Transport (DfT) in 2019, stated the UK Government’s ambition that “By 2050, the UK will actively drive the transition to zero emission shipping in its waters. (UK Department for Transport, 2019)

Another report prepared for the United Kingdom Department for Transport focused on the future technologies and the current technologies available within the shipping sector in order to minimize the emissions caused by shipping and aimed to provide guidance and decision support for policy makers. This report concluded that the sector should put an end to use of fossil fuels by 2030 in order to comply with the UK Government's Maritime 2050 policy. (UK Department for Transport, 2019)

Concerning the future requirements and demands, a study has also been published by the UK Department for Transport (DfT) and titled Potential Demands on the UK Energy System from Port and Shipping Electrification, focused on 10 biggest shipping ports which represents the 70 percent of total in United Kingdom (UK) and comparing the future energy demand by ports under current technology infrastructure and then the electrified fleets scenario. (UK Department for Transport, 2019)

Considering these works and new policies together with the pre-defined Emission Control Areas within MARPOL Annex VI, it is obvious that some countries and non-governmental organisations have already stepped forward and for sure many more will follow in the near future in order to comply with the regulations and contribute to the global fight to lower the emissions caused by the shipping sector.

2. MATERIALS AND METHODS

As already mentioned in the previous sections the aim of this study is to develop an open source energy and emission analysis tool specific to shipping industry. Building the tool benefitting the open source programming has been considered vital as the secondary aim is to keep the tool resilient and free for further developments and studies. Before starting to develop the tool, a superficial review on the tools available has been conducted. As a result of the review, although there are some of them providing support for academic studies for free, almost all tools available have been identified as commercial and not specific to the ship energy systems. Between the eight tools reviewed, only one of them identified as benefitting the open source programming but again not specific to ship energy systems.

In this regard, another generic review has been conducted in order to decide on the programming language and the platform to be used.

In a report (GitHub-The State of Octoverse, 2020) published by GitHub which is a platform for open-source programmers and owned by Microsoft Inc., Java Script, Python and Java programming languages have been placed as first three of other programming languages in 2019. Considering the latest curve upwards it succeeded and having a huge amount of data science libraries Python Programming Language has been chosen since the secondary objective for this tool is to be able to make data driven analysis. Python programming language is frequently used for artificial intelligence applications and data science which are essential for energy industry analysis.

3. RESULTS AND DISCUSSION

3.1. Development Process

As all kinds of engineers are focused on optimizing a system, collecting and utilizing more data as we can is an important factor to get better results from analysis. However engineers are already familiar with complex software tools, this study anticipates to build a more user friendly tool which can be used even by a mechanic employed on board a ship who can be considered as the end user of the shipping industry. In this regard, parameter amount required by the tool kept low however some additional parameters have already been included to be used with possible future studies.

3.1.1. Defining the Software Architecture

The main objective has been set as to provide all the information will be needed in order to let the tool build and visualize a ship's reference energy system. In this regard a database has been designed to hold the information of primary and second energy carriers, conversion technologies together with end use technologies on board ships.

Considering the possible need by future researches; another database table has been defined to hold generic data of multiple ships. Once technologies identified in relevant database modules, user should be able to create a new ship as a new database item and include pre-defined technologies on their new-defined ship. Thus, tool will be able to understand the relations between the equipment on board the ship. In other words, tool will now have the reference energy system so it can bring it forward by visualising the reference energy system. Some additional specifications are already defined for the reference energy system considering the future researchers who would want the tool to apply specific analysis and/or scenarios on the system. In this regard Sankey diagram has been chosen to visualize the reference energy system. Sankey diagram has been widely used for visualising energy flows throughout energy systems. Later step has been identified as to design a module which the user can enter data specific to a voyage and then let the tool calculate Energy Efficiency Operational Index (EEOI) for the voyage.

Concerning the Energy Efficiency Design Index (EEDI) tool, additional literature review conducted and some sceptical studies were identified.

Nikoletta L. Trivyza, Athanasios Rentizelas and Gerasimos Theotokatos studied on comparative analysis of Energy Efficiency Design Index (EEDI) versus lifetime CO_2 Emissions of ships. This study claimed that EEDI underestimates the effect of technologies for reducing carbon emissions in all the investigated cases and promotes use of lower installed power in order to reduce the emissions. The study also concludes that EEDI is a conservative metric, which however can be used as an approximation to compare alternative solutions early in the design phase. (Trivyza, Rentizelas & Theotokatos, 2020)

In this regard EEDI calculation disregarded for this study since it also aims to help engineers and ship builders during the design phase and there are already some studies claiming that EEDI is not practical in some cases.

3.1.2. Designing the Interface

The modules decided to be developed, coded via using different Python libraries and new written codes. Considering the availability of internet, the tool designed to work on the Web. In doing so, it is aimed to avoid possible installation and compatibility issues which may occur while working on different operating systems.

3.1.3. Designing the Database Modules

Four database tables and concurrently four modules have been created in order to let the user build their own reference energy system. Although there is no mandatory order for the database tables to be filled it is suggested to follow primary energy carriers, conversion Technologies, enduse technologies and ship database fields order.
On the primary energy carrier module, user is required to provide necessary parameters like name, stored energy and efficiency for the primary energy carriers such as fuel tank or batteries. Although there is no energy conversion operation by the primary energy carriers, an efficiency parameter has also been defined in order to calculate possible losses which may occur during long storage periods.

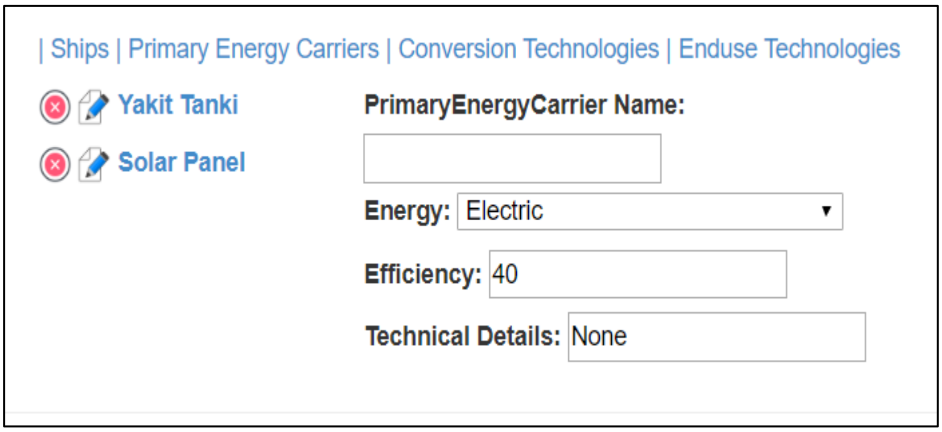

Figure 2. Primary energy carrier module user interface.

User is required to provide following parameters shown in Figure 3 to define conversion technologies such as main diesel engines, generators, boilers, electrical converters etc. Label, source energy, energy consumption per hour, output energy, efficiency, on time percentage and SO_x, NO_x, CO_2 emissions should be defined as initial parameters. Although it's not used for the time being, 'on time percentage' parameter has already been defined in order to give the future researchers the opportunity to build modules for hourly or daily basis analysis on the reference energy system.

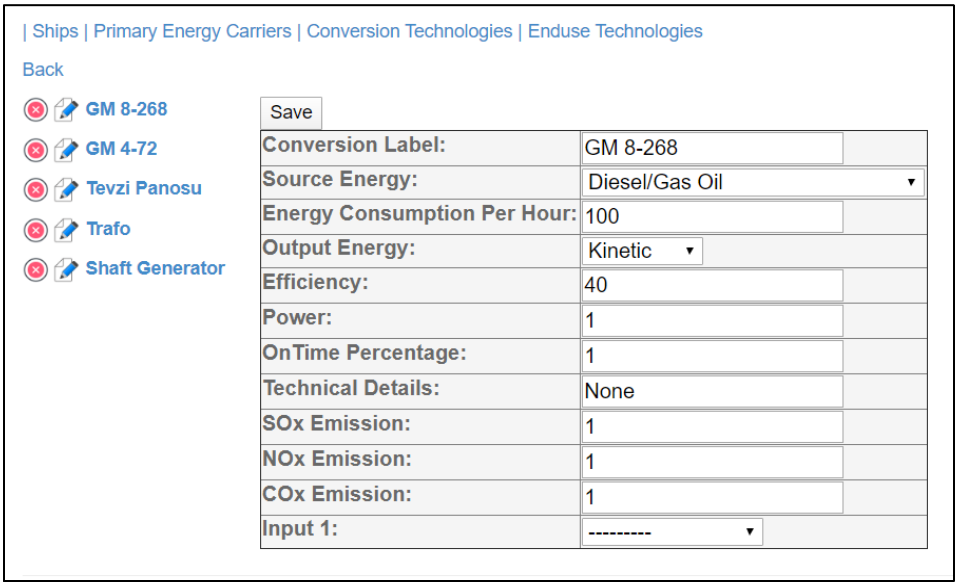

Figure 3. Conversion technologies module user interface.

Same parameters have been defined for the enduse technologies. However, both conversion technologies and end use technologies have the same parameters; these two considered as two different technology groups to let the software tool understand their classification while building the reference energy system.

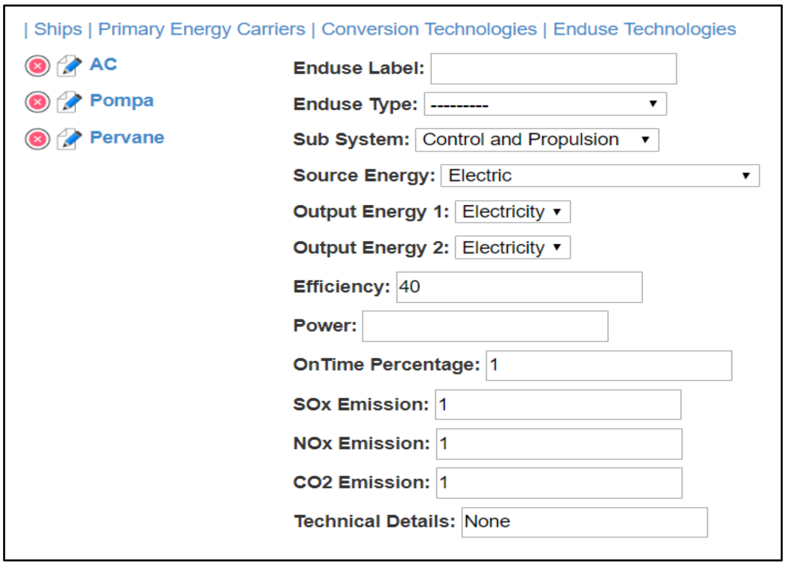

Figure 4. Enduse technologies module user interface.

Once technology databases are defined user will be able to define a new ship with basic parameters such as ship name, IMO number, area of operation, date of commission, displacement, Length over all (LoA) and Beam over all (BoA). Since the technologies are already defined now the user can pick which equipment to be included to the system from the primary energy carriers, conversion technologies and enduse technologies. As the last step user should define relations between this equipment on board in order to describe the energy transfers throughout the reference energy system.

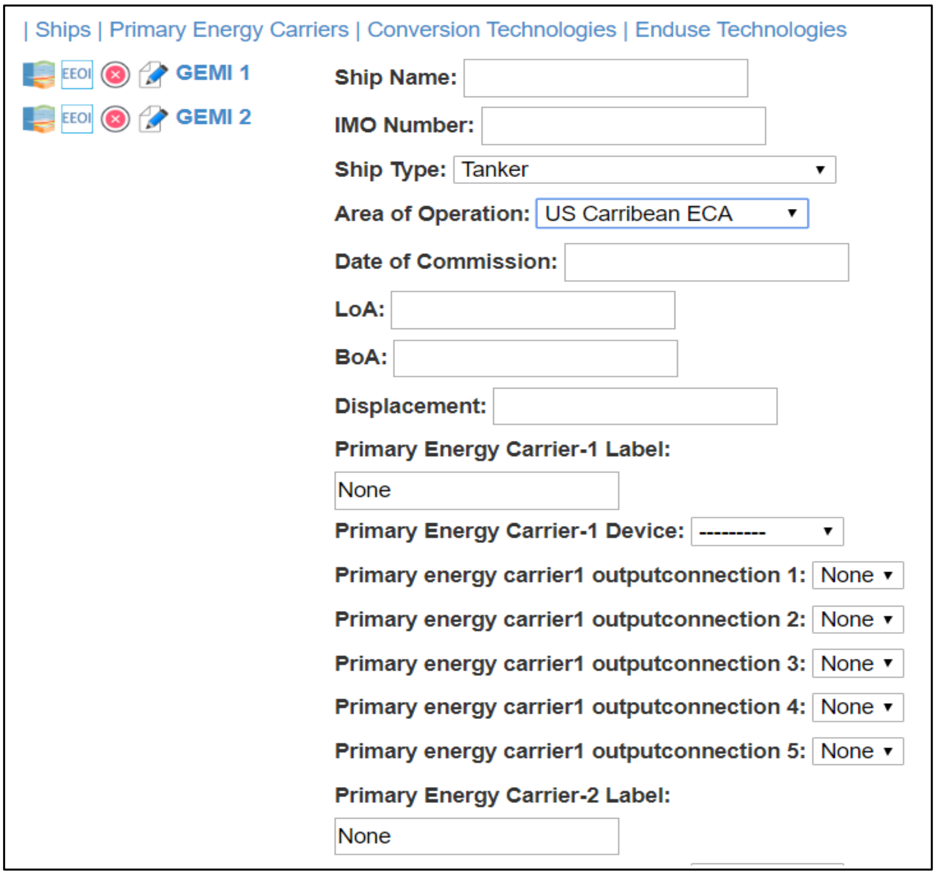

Figure 5. Ship database module user interface.

After all the equipment is associated with the ship, user will be able to visualize the reference energy system by clicking the Sankey diagram link. Figure 6 shows the visual output of the reference energy system created for a hypothetical ship named MV Hasan Pasa. The Sankey diagram module lets user to highlight a specific flow or hub and view details when the cursor hovered on them. Thus, it creates an easier view and makes it more user-friendly even when the reference energy system gets complicated owing to the big numbers of equipment associated with the ship.

The EEOI module as shown in Figure 7 requires user to provide parameters needed specific to a voyage to be able calculate EEOI value. Once the user provides the cargo carried, distance sailed, fuel types and amounts consumed during the voyage, the module calculates the EEOI value using the Equation 1 provided within International Maritime Organization (IMO) guidelines.

$$EEOI = \frac{\sum_j FC_j \times C_{F_j}}{m_{Cargo} \times D} \quad \textbf{(1)}$$

In this equation *FC* stands for amount of fuel consumed in metric tonnes (mT), m_{Cargo} stands for the mass of cargo carried, *D* stands for the distance sailed in nautical miles (NM) and C_F is Fuel mass to CO_2 mass conversion factor specific to fuel type consumed. C_F is a non-dimensional conversion factor derivates from fuel consumption measured in a unit of gram and CO_2 gas emission measured in gram based on the carbon content. C_F values defined for specific fuel types are shown in Table 1.

Table 1. Conversion factor (C_f) for fuel types (Adapted from IMO Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator).

Type of Fuel	Reference	Carbon Content	C_F $(t\text{-}CO_2) / (t\text{-}Fuel)$
Diesel/gas oil	ISO 8217 Grades DMX-DMC	0,875	3,206000
Light fuel oil (LFO)	ISO 8217 Grades RMA-RMD	0,86	3,151040
Heavy fuel oil (HFO)	ISO 8217 Grades RME-RMK	0,85	3,114400
Liquefied petroleum gas (LPG)	Propane butane	0,819 0,827	3,000000 3,030000
Liquefied natural gas (LNG)	LNG	0,75	2,750000

4. CONCLUSION

As explained in the previous sections and already proved by scientific and academic studies; transport and specifically the shipping sectors are one of the main contributors of the global emissions. While shipping sector represents a substantial portion of global air pollution cake, it can also be considered as an important factor for local and global economies.

Having both economy and air pollution issues together on the scale shipping sector needs to be resilient in order to balance pros and cons and maintain their profits while also complying with the air pollution regulations.

While sector is facing challenging times due to the latest regulations promulgated, some governments and non-governmental organizations already stepped forward by conducting new studies and setting new objectives to be able to comply with the regulations on energy efficiency and emissions of ships. This is an obvious indicant showing that all the stake holders of the sector varying from design engineers, ship builders, ship companies, ship owners and the ship operators on board ships should immediately focus on optimizing and operating their systems in line with the regulations.

Since optimizing a system is the main purpose of all the engineering studies, engineers have been widely benefitting the computer technologies by utilizing enhanced software tools for the last decades. Considering the need and the dependency for data of energy sector one can say that the shipping sector for sure will need new, resilient and 'specific to sector software tools' as embodying comprehensive and complicated energy systems in other words, ships.

As depicted in this study, there are already available software tools for the energy analysis but not many of them are practical for the shipping sector and also most of them are commercial and not focused on ships directly.
In this regard, this study anticipated to touch the base for a resilient, comprehensive and user-friendly open source web tool for the stake holders of the shipping sector which can help them to conduct energy and emission analysis on their fleets.

Choosing open source programming for coding and Web as the platform have been considered necessary to keep the tool widely available and open to further enhancements by future researchers and programmers. Some possible future developments on the tool already taken into account and additional parameters have been amended to database tables.
Having a wide range of free and available libraries and being one of the most popular open source programming languages, Python programming language has been chosen to build the tool however new coding also required during the development phase.

In the design phase, a database has been defined which will hold the data of primary/secondary energy carriers, conversion and endues technologies in other words all the equipment on board ships. In addition, a database table also defined to hold the ship's data which also lets user to create multiple ships.

Following the design and the coding phases, an imaginary ship and some technologies had been defined on the database by using realistic data to test and showcase the results given by the tool. Once the technologies associated with the ship and the relations between technologies defined, Sankey diagram visualising the ship's reference energy system acquired as shown in Figure 6 and the diagram rendered the reference energy system correctly by visualising all the energy flows and emissions. As the last step, imaginary voyages had been added to ship's voyage history and the tool calculated the Energy Efficiency Operational Index (EEOI) which is a great tool to analyse a ship's energy efficiency while keeping the emissions between limits. This will further give an idea to ship operators of how to optimize voyages in terms of cost efficiency and the emission of a ship.

Overall, the developed tool has been considered as achieved the main objectives of this study. Providing the opportunity for the future researchers to enhance the tool is considered as a great take away. Future studies can bring new modules to life which will let the user to conduct analysis on a ship's reference energy system and visualise the system with more details such as hourly and/or daily basis energy analysis also having the ability to detect abnormalities within a ship's energy system and provide recommendations in order to fix the limping part of the system.

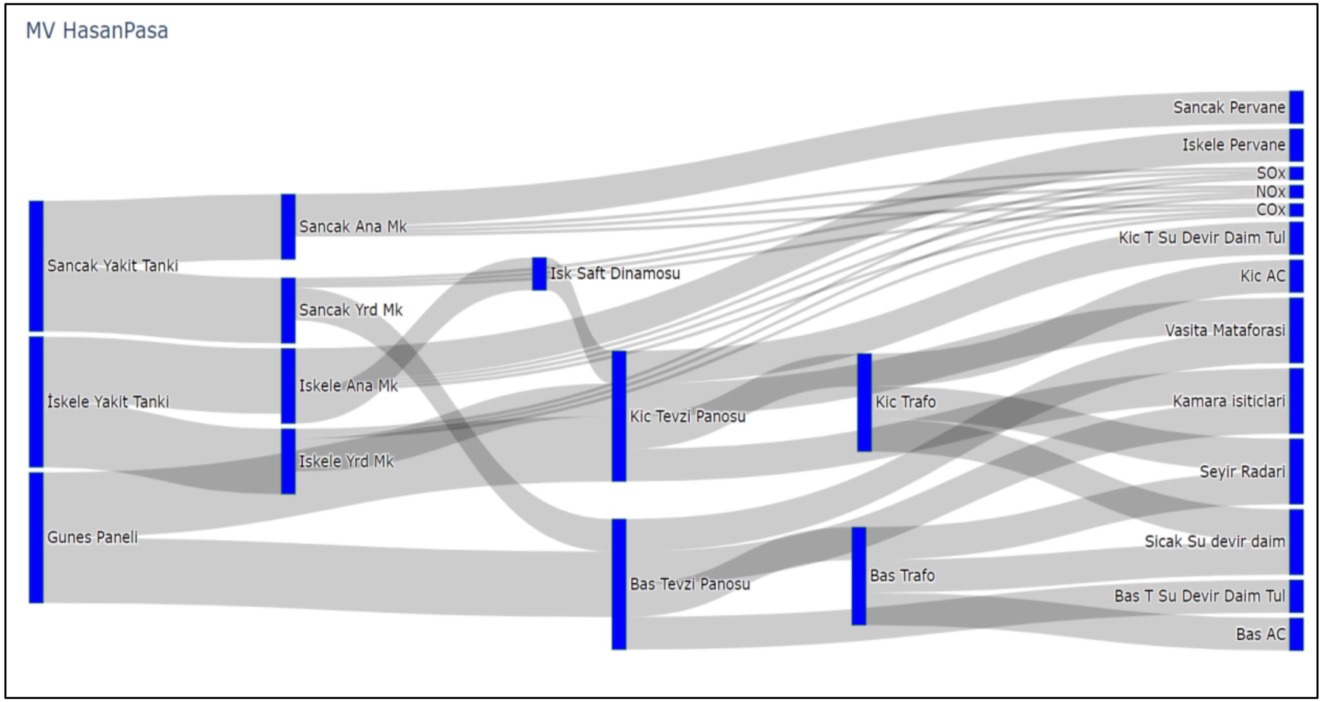

Figure 6. Reference energy system output for the imaginary test ship M/V Hasan Pasa.

| Ships | Primary Energy Carriers | Conversion Technologies | Enduse Technologies

MV HasanPasa Voyages

Voyage Name:	Libya KKTC
Voyage Date:	2020-02-19
Cargo:	100
Distance:	900
Fuel1:	Diesel/Gas Oil
Fuel1 consumption:	411
Fuel1:	Diesel/Gas Oil
Fuel2 consumption:	0
Fuel1:	Diesel/Gas Oil
Fuel3 consumption:	0

Submit

Voyage Name	Date	Distance(NM)	Cargo Carried	Fuel1	Fuel1 Consumed(MT)	Fuel2	Fuel2 Consumed(MT)	Fuel3	Fuel3 Consumed(MT)	EEOI
Canakkale Mersin	2020-02-09 00:00:00+00:00	400	530	Diesel/Gas Oil	120	Diesel/Gas Oil	0	Diesel/Gas Oil	0	0.0018147169811320754
Mersin Libya	2020-02-14 00:00:00+00:00	400	1200	Diesel/Gas Oil	615	Diesel/Gas Oil	0	Diesel/Gas Oil	0	0.0041076875
Libya KKTC	2020-02-19 00:00:00+00:00	100	900	Diesel/Gas Oil	411	Diesel/Gas Oil	0	Diesel/Gas Oil	0	0.014640733333333333

Figure 7. EEOI output for the imaginary test ship M/V Hasan Pasa**.**

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