Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole?

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Abstract

This paper was inspired to answer the fundamental question on whether electric battery powered ships can ultimately be a promising solution for future maritime environmental protection. The overall process was designed to demystify the holistic environmental benefits and harms of 14 primary energy sources for electricity production in consideration of the national-specific cases of 33 countries. A series of comparative analyses between the diesel as the reference fuel and the battery-electric propulsions were conducted with 27 short-route ferries engaged in Scotland coastal areas. A key message obtained from the analysis results were that the impact of battery application was far from the zero-emission shipping in the lifecycle perspective. Moreover, the same vessels were found to yield completely different environmental performances, depending on how those countries produce electricity. In some Asian countries heavily relying on fossil-based power generation, the environmental impact of battery operation was estimated far greater than that of diesel operation in the UK. Case studies were, then,

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scaled-up to about 5,500 marine vessels presently engaged in international voyages. In general, consistent results were found. Research findings distinctively demonstrated the misguidance of current maritime policies for encouraging battery-powered ships and identified that these shortcomings would stem from the limitations of current practices of maritime environmental assessment. Lastly, it strongly suggested to the marine industry and stakeholders that the environmental protection from shipping activities would be not only a matter of ships but also a matter of how the national power grid develops.

Keywords: battery-powered ships: life cycle assessment: battery ships: electric propulsion: marine decarbonization: marine fuels

1 Introduction

Given that shipping highly relies on fossil-fuel combustion contributing significantly to air pollution, the transition of those conventional fuels into alternative clean energy sources has been recognized as an urgent global issue (IMO, 2018a). With such an increasing pressure on cleaner shipping, the International Maritime Organization (IMO) has reached a series of ambitious agreements on the reduction of maritime greenhouse gas (GHG) from merchant vessels. In 2018, in particular, the Organization has adopted the Resolution of MEPC.304 (72) that introduces a remarkably ambitious plan known as 'initial IMO strategies' aiming at reducing minimum 50 % GHG by 2050, compared to the 2008 level (IMO, 2018b). To achieve this 2050 target, marine vessels are urged to go away with conventional oil products while to adopt low or carbon free energy sources. The use of battery systems in place of diesel engines is now emerging as one of the most realistic solutions to achieve the global 2050 target (Yang et al., 2020; Yang et al., 2021). Unlike diesel, it is because the electricity stored in the battery can produce no emission during the voyage. In addition, a battery application can guarantee many other advantages - such as relatively simple and lower operating and maintenance costs over diesel systems - that attract more and more attention to the battery powered ships (DNV GL, 2019).

The first battery-powered ship was a Russian tanker, MV Vandal, launched in 1903. Despite its long history, due to various technical difficulties until recently, modern battery ships (including diesel-electric hybrid ships) generally fall into small categories of cruise ships and icebreakers. Nevertheless, over several decades, numerous efforts have been made to improve the battery technologies across industries (Aaldering et al., 2019). As results, the performance of power converters (Chiang et al., 2019), semiconductor devices, transmission (Jiang et al., 2021) and storage (Mehrjerdi and Hemmati, 2019) has been greatly improved. With no exception, the marine industry has strived to implement battery powered ships through innumerable R&D works. The past research, meanwhile, has primarily directed to promoting the control method of battery electric propulsion system in several ways. Some studies on optimal battery controls for marine vessels are noteworthy. Zhu et al. (2014) proposed an energy management strategy based on fuzzy logic for hybrid vessels combining proton exchange membrane fuel cells (PEMFC) batteries with ultra-capacitors (UC). Simulation results revealed that optimal performance with high efficiency of hybrid systems could be achieved by reducing the dynamic ship load. Bassam et al. (2016) presented a method of determining the power capacity of a domestic ferry adopting hybrid fuel cells and batteries. The focus of the study was on minimizing operating and maintenance costs for those systems. The power requirements of the ferry were calculated using the proven time domain three degrees of freedom full ship system simulator implemented in the MATLAB / Simulink environment. Alafnan et al. (2018) proposed a hybrid energy storage system (HESS) that would be useful for all electric ships to reduce the impact of system load fluctuations on system efficiency and to maintain bus voltage. It has been proven to improve the quality of the power grid by developing AES grid model integrated with SMES and battery. Lan et al. (2015) conducted a research on optimizing the benefits of photovoltaic (PV) panels on a large oil tanker ship system in terms of economic and environmental perspectives. Zhou et al. (2021) proposed an effective control model of hybrid system applicable for an ice-breaking ship.

The number of battery-powered vessels, backed by such remarkable research, is growing rapidly around the world. According to DNVGL (2019), as of March 2019, more than 150 battery-powered ships (about 20 for full battery-powered ships and about 140 for battery hybrid ships[1]) around the world have been launched as shown in Fig. 1. It has grown significantly compared to 1998, when only one vessel was operated with the battery system. Moreover, this incremental trend is highly expected to continue year after year.

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[1] ships that are designed to operate on battery power or some other form of hybrid setup such as diesel engines.

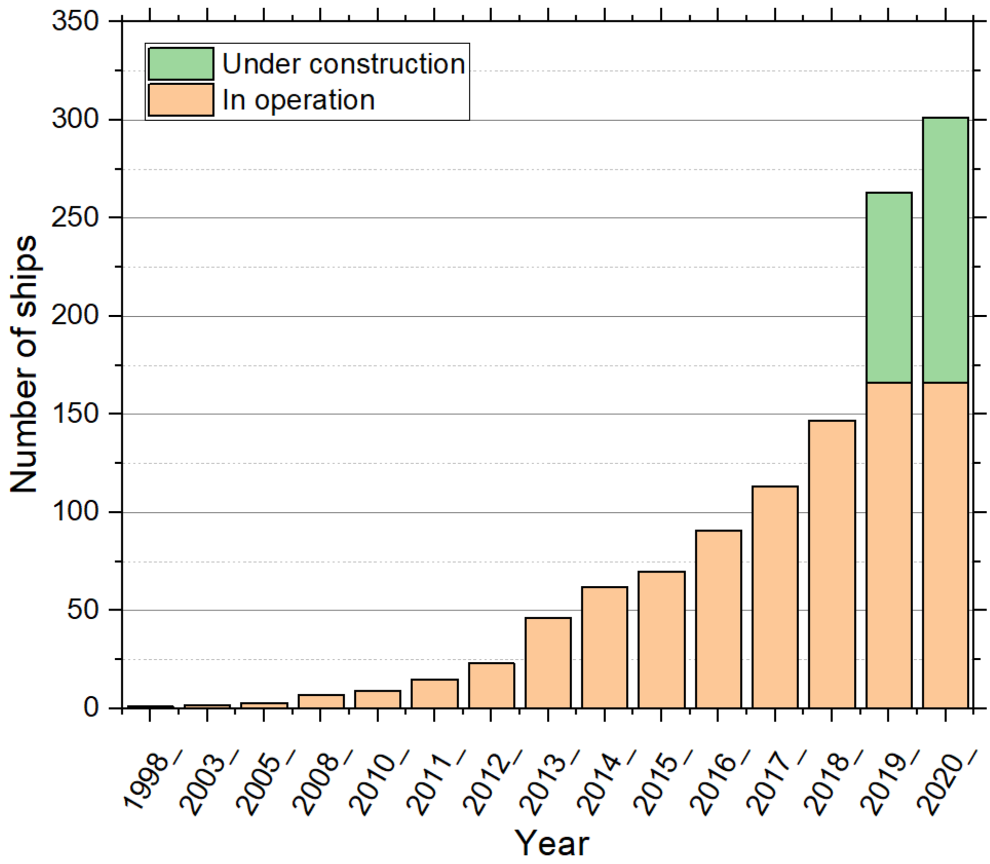


Fig. 1. Battery-powered ships in service and in order as of February 2019 DNVGL (2019).

Meanwhile, the consequences of fossil fuel burning has brought out serious concerns about the air pollution, not only CO_2 but also other pollutants such as SO_x, NO_x and particulate matter (PM) across industries (Sims et al., 2003). Those concerns urge to harness sustainable energies for electricity generation. Unlike coal and natural gas, alternative energies can contribute to producing electricity without releasing large amounts of emissions. Fig. 2 shows the CO_2 equivalent emission levels from various energy sources for electricity generation (World Nclear Association, 2021).

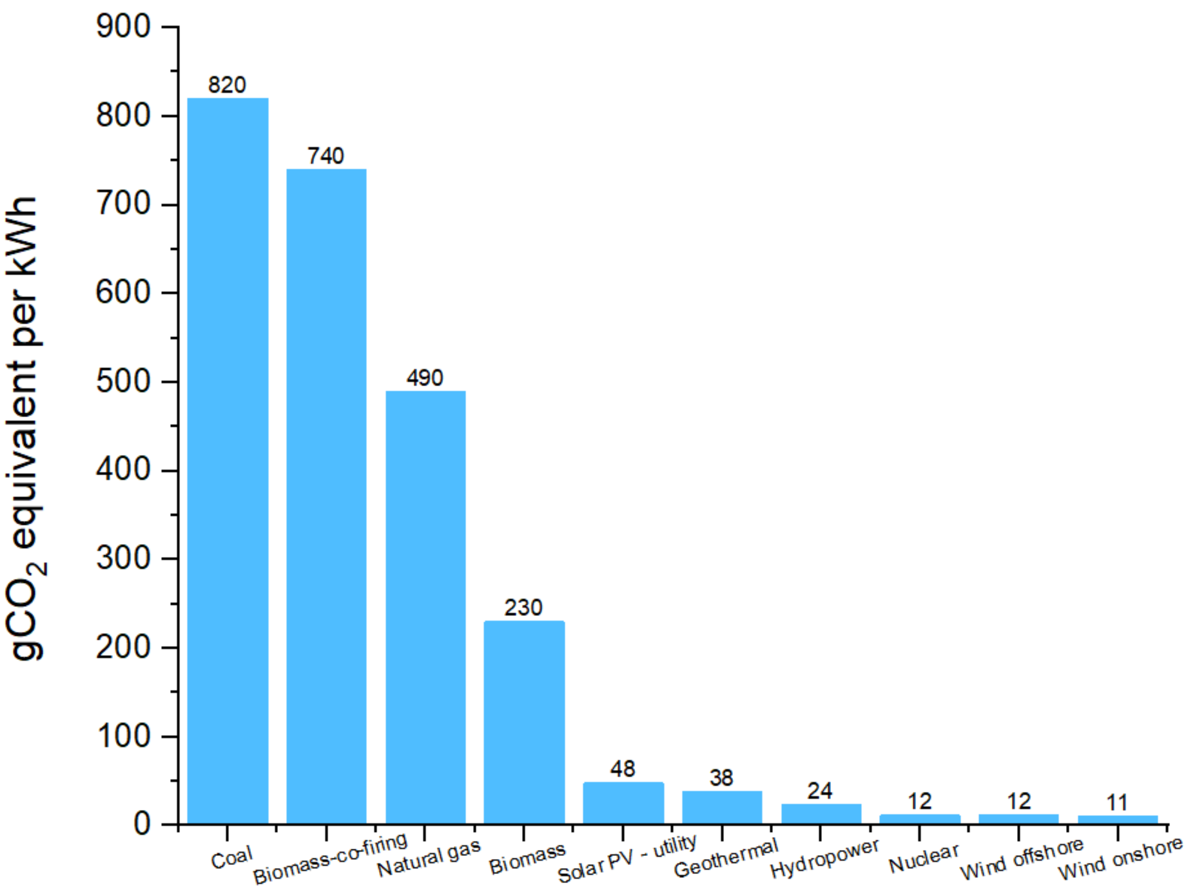


Fig. 2. CO_2 eq. emissions for electricity generation by various fuel types (modified based on (World Nclear Association, 2021)).

This fact offers us an insight into the battery ship itself to be neither beneficial nor harmful. Key factors will be the methods that determine what primary energy sources are used for electricity production. In a developing country, an electric vehicle may run on the electricity generated from coal, whereas, in a developed country, like Norway, the same electric vehicle can be driven by the electricity generated from relatively harmless hydro or other renewables. Fig. 3 shows that the conventional carbon-based fuels, such as coal, natural gas and oil, account for 64% of total energy; their contribution is still in a large part of world electricity generation.

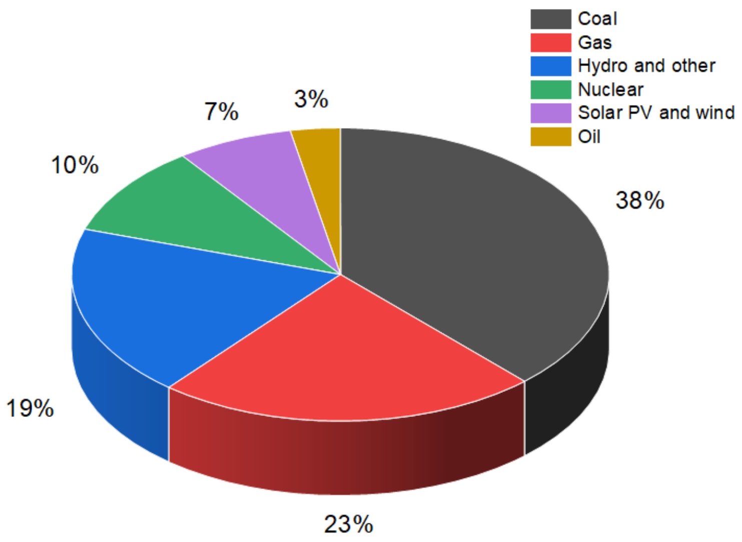


Fig. 3. 2018 World electricity generation (26,700 TWh) (modified based on (IEA, 2019)).

This fact raises the question, as mentioned in Fig. 4, where this paper aimed to determine whether battery-powered vessels are ultimately a cleaner option over conventional diesel ships or whether those vessels are rather harmful than helpful to humanity through a compelling analysis. To achieve this goal, this project was proposed to accomplish the following objectives: 1) identifying research gaps and seek an appropriate method and input data from past research; 2) implementing lifecycle assessment to evaluate the distinction of holistic environmental impacts pertaining to various energy sources used for electricity generation which would be fed into battery powered ships as the main power source. 3) proposing case studies with all credible electricity production scenarios; 4) quantifying the holistic emission gaps among the different primary sources for electricity generation and determining how those gaps can contribute to the environmental performance of battery-powered vessels. 5) discussion and confirmation on the key findings to answer the fundamental question.

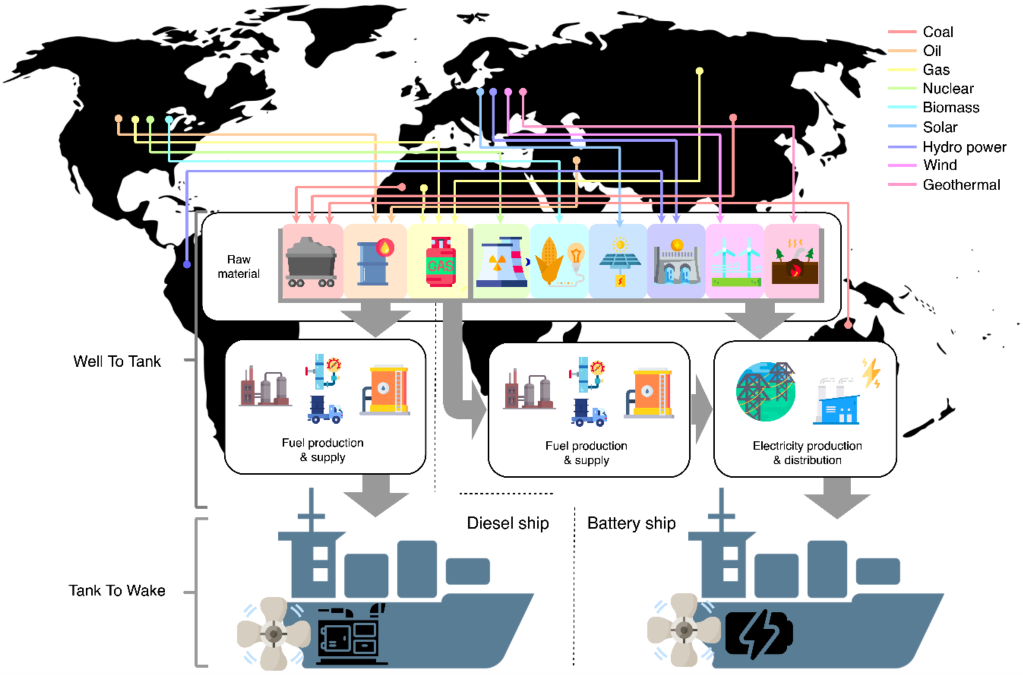


Fig. 4. Fundamental question risen in this paper; are battery-powered ships ultimately greener than diesel ships?

To achieve the objectives established, the structure of this paper was proposed as follows. **Ch.2** will explore the past research and identify research gaps. Based on the lessons from the past research, the research methodology will be established in **Ch. 3**. The proposed method will be applied for a series of case studies through **Ch. 4**. Study results, original contribution to the industry and the guidance on future studies will be further discussed in **Ch. 5.** Finally, key findings will be encapsulated and highlighted in **Ch.6**.

2 Literature review

In terms of environmental benefits derived from marine battery applications, most of the past research and publications have confidently suggested that battery-powered ships will be a proper solution to achieve ‘zero emission target’. For instance, ICS (2021) described the battery method a key game-changer which would contribute to a zero emission blueprint for shipping sector. Reusser and Pérez Osses (2021) also introduce the battery powered ships as zero emission vessels while addressing technical challenges of their marine application. Indeed, there are voluminous publications that describe battery-powered ships as 'zero-emission ships' but will not be further presented in this paper.

On the other hand, there have been a few attempts to holistically evaluate the environmental performance of battery-powered ships by expanding the scope of analysis towards the lifecycle perspective. As some pilot studies, the comparative analyses of battery-powered systems to conventional diesel-mechanical and diesel-electrical propulsion systems for a UK short-route ferry were conducted by Jeong et al. (2018a); Jeong et al. (2018b). That research also introduced an enhanced process to facilitate the use of LCA in the marine industry. In addition, Ling-Chin and Roskilly (2016) investigated the impact of a new build battery-powered system on a roll-on / roll-off cargo ship from a lifecycle view. The emphasis of the research was placed on the comparison of the life cycle of the battery system and the diesel engine in consideration of system manufacturing, operation & maintenance onboard and decommission. The excellence of battery-powered ships was proven through them and the results are in the same line with the LCA research on battery application for automobile sectors: a series of environmental impact studies for electric vehicles (Ahmadi, 2019); investigation of the size and range effect (Ellingsen et al., 2016); comparative analysis with diesel cars (Petrauskienė et al., 2020); Extensive literature review on cost and emission of load vehicles (Wolfram and Lutsey, 2016); Comparison of diesel and electric vehicle for Chinese case (Yang et al., 2021).

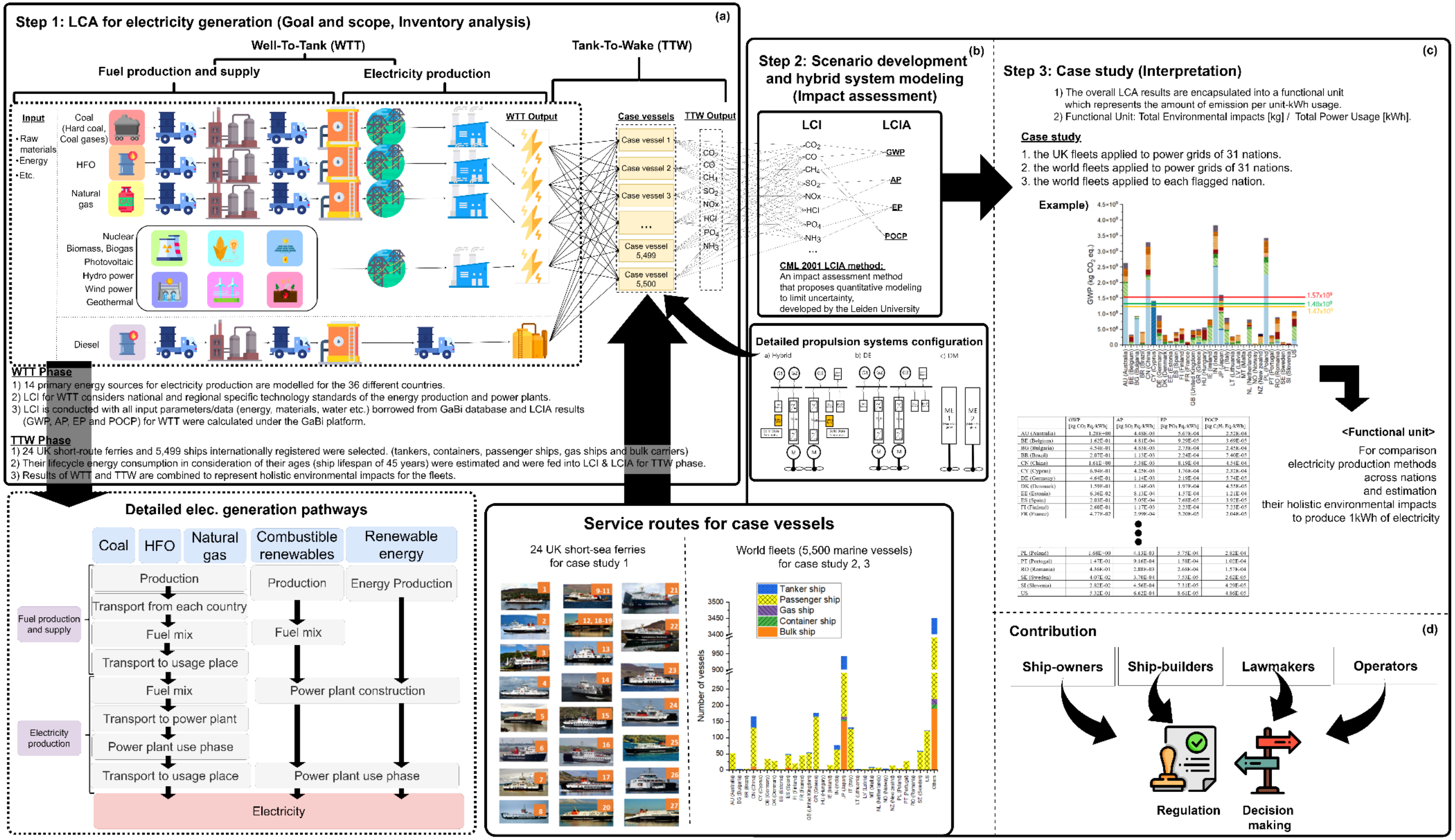
Meanwhile, when assuming the electricity is supplied from the shore to onboard via plug-in connection, the use of battery requires additional activities for the electricity production which may lead to a potential increase in emissions at the electricity production stage. Thus, it can be argued that battery-powered ships may merely pass the environmental impact onto electric utilities rather than removing it entirely. Even if we can see the environmental benefits of battery-powered ships, there will still be a big difference in emission reduction levels, depending on the ways of electricity production and supply to ship. While it is an urgent issue for the success of battery-powered ships, the past research has not been able to answer this fundamental question regarding such trade-offs.

In this regard, some past studies have been conducted to quantify those trade-offs. Here are some examples. Perčić et al. (2021) conducted a comparative analysis for two different power system designs: a battery-powered and diesel engine-powered ones. The research findings revealed that diesel engine-powered ship would emit more than twice CO_2 per each nautical mile sailing than battery option. On the other hand, the ship's service area was Croatia that utilizes high level of hydro and bio energies for national power generation. This study raises the question of whether the same results could have been achieved if the service area was different. A similar study can be found in Wang et al. (2021) estimating a short route ferry within riverbank of England and the LCA results suggested the environmental benefits of battery applications. A limitation of these studies is that the case scenarios proposed in those papers was highly in favor of battery powered vessels, as battery power comes largely from renewable sources. On the other hand, there are few studies examining the environmental impact of battery-powered ships operating in countries that are highly dependent on coal or other types of fossil fuels. Given this, there was no direct comparison/indication of the impact of primary energy sources on the overall environmental impact for the battery-powered ships. Therefore, the authors were convinced that it would be worthwhile to seek for the answer by investigating the influence of power sources to the environmental performance of battery-powered vessels using the LCA method.

3 Evaluation framework

To answer the fundamental question presented in the previous sections, or at least get closer to the answer, this section proposes the step-by-step approaches relative to the objectives defined in Ch.1. Fig. 5 presents the outline of the whole research process and steps conducted in this paper. It consists of three steps: 1) LCA for electricity generation; 2) Scenario development and hybrid system modelling; 3) Case study.

Step 1 was firstly proposed to evaluate the distinction of holistic environmental impacts pertaining to various energy sources used for electricity generation which would be fed into battery powered ships as the main power source. Step 2 was designed for scenario development and hybrid system modeling with case ship selection. In Step 3, LCA was applied to the case ships as well as international marine fleets to observe their environmental performances under various scenarios. The process of comparative analysis and its outcomes would be interpreted in a way to answer the fundamental question; *'are battery-powered ships truly the solutions for marine environmental protection as a whole?'* Further details of each step will be discussed in the sections to follow.

1 

2 Fig. 5. Outline of the whole research process and steps.

3.1 Step 1: LCA for electricity generation

3.1.1 Identification on energy sources/methods for electricity generation

Electricity is produced from various sources of primary energy. As dictated in Fig. 3, the underlying sources of electricity in the world were accounted for coal 38%, natural gas 23%, hydroelectric 19%, nuclear power 10%, oil 3% and solar/wind 7%. Given that the cleaner production of the electricity is highly dependent on its primary sources, the differences in the composition of raw energy sources among countries are likely to lead to remarkable distinctions as to the environment. For instance, according to Fig. 6 showing energy share (%) for electric generation across 36 countries, the Norway uses less than 5% of fossil fuels for the national electricity grid, but the US uses them more than 60% and China has them over 70% (IEA, 2019). It further leads to the inference that two identical battery-powered ships would result in completely different environmental performance, depending on where those ships are being operated. In this context, the major energy sources for world power distribution were categorized so that a total of 14 energy sources[2] were found to be mostly used for electricity generation across 36 representative countries[3] (IEA, 2019).

[2] heavy fuel oil, natural gas, biomass, hard coal, biogas, lignite, coal gas, peat, nuclear, photovoltaic, waste, geothermal, wind and hydro power.

[3] AT (Austria), AU (Australia), BE (Belgium), BG (Bulgaria), BR (Brazil), CN (China), CH (Switzland), CY (Cyprus), CZ (Czechia), DE (Germany), DK (Denmark), EE (Estonia), ES (Spain), FI (Finland), FR (France), GB (United Kingdom), GR (Greece), HU (Hungary), IE (Ireland), IN (India), JP (Japan), IT (Italy), LT (Lithuania), LU (Luxembourg), LV (Latvia), MT (Malta), NL (Netherlands), NO (Norway), NZ (New Zealand), PL (Poland), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), SK (Slovakia), US

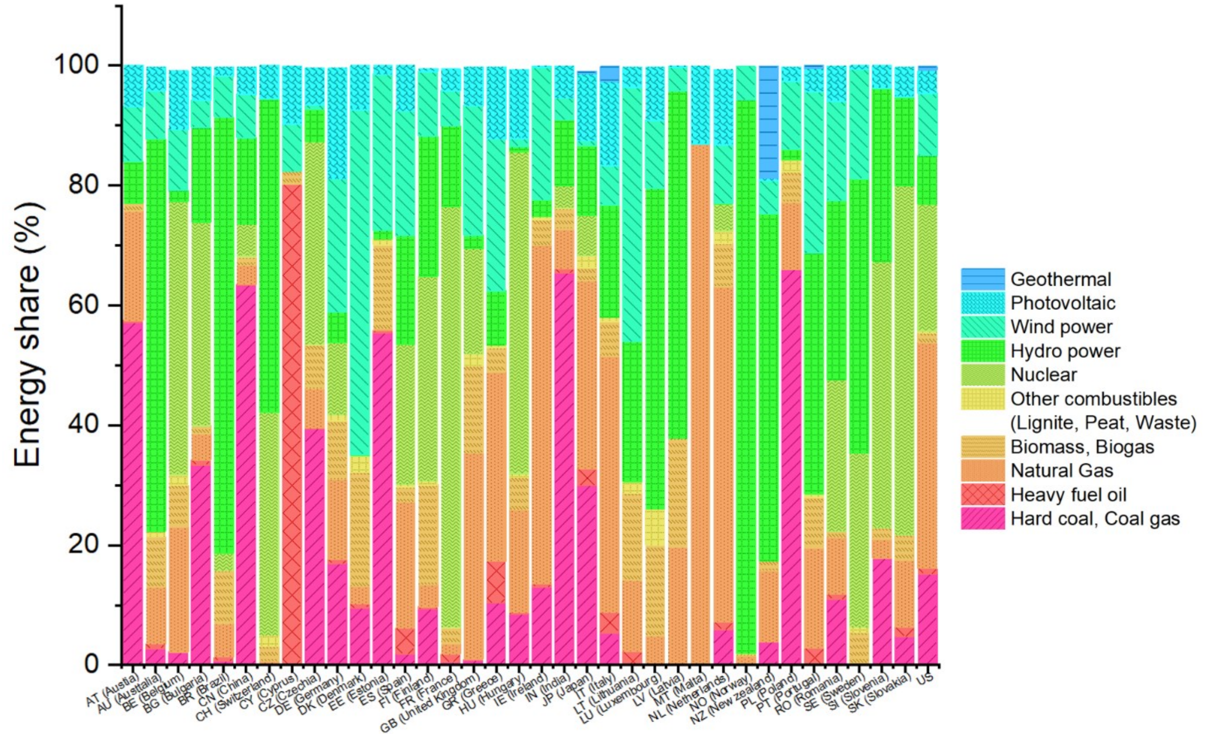


Fig. 6. Energy share (%) for electric generation for 36 countries (IEA, 2019).

3.1.2 Data collection and LCA modelling

To estimate the holistic environmental impacts of the electricity generation via the 14 identified primary energy sources, LCA models have been developed in the platform of GaBi Software 2020. Based on cradle-to-gate approach, Fig. 7**Error! Reference source not found.** shows the life cycle pathway of each energy in the range from raw material extraction to the electricity production. It is largely composed of two sub-stages: ‘fuel production’ and ‘electricity production’. The pathways developed in this research were referred from the GaBi database that has been developed from extensive industrial investigation and evaluation, taking into account all the characteristics of the individual country situation (Sphera, 2020).

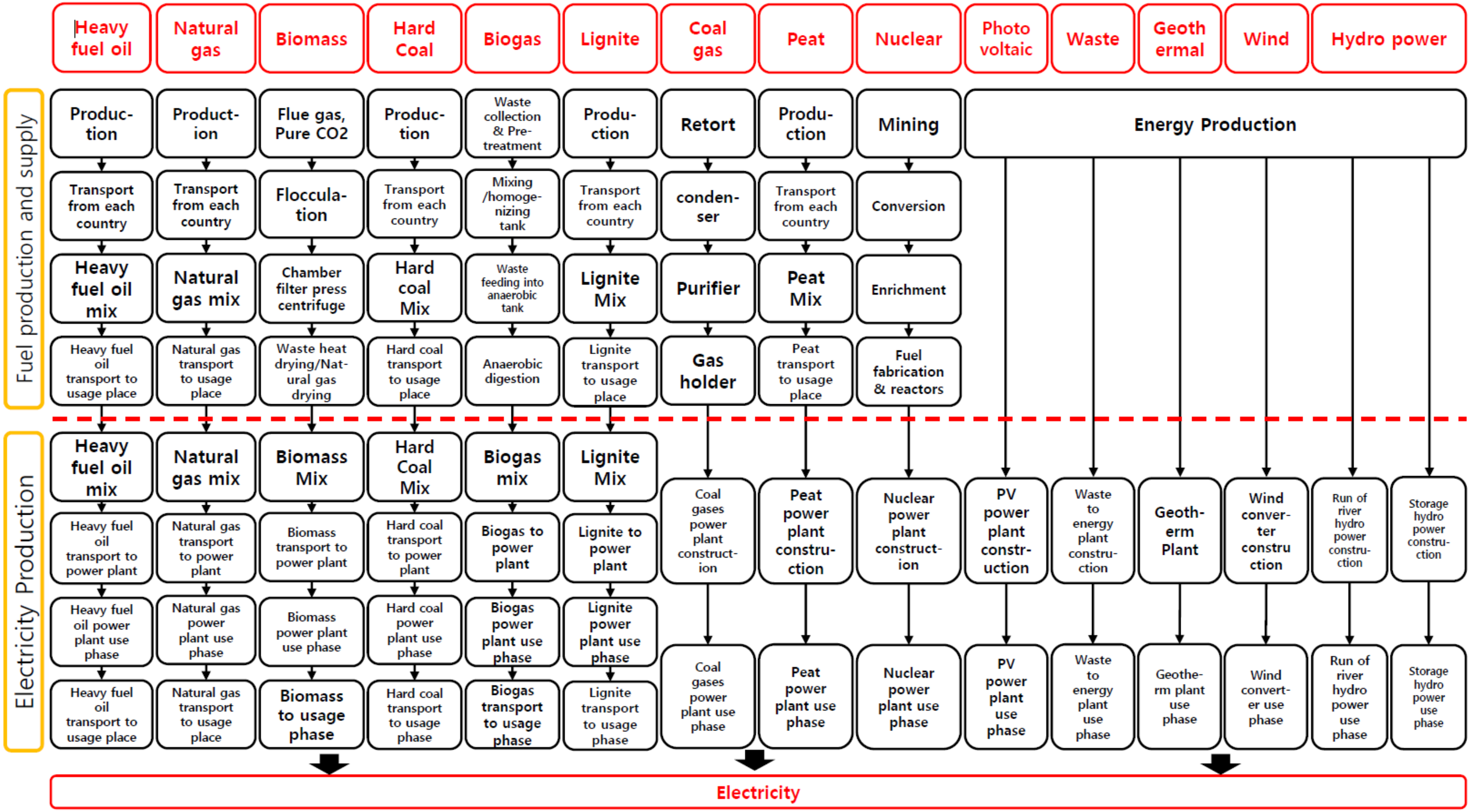


Fig. 7. Electricity generation process from various energy sources.

The LCA models developed for the candidate energy sources are detailed as below:

(a) Heavy Fuel oil (HFO)

HFO is the result or residue of the distillation and cracking process of petroleum which is mostly recovered by oil drilling beneath the Earth's surface. Through the refinery process, the petroleum is separated into various types of fuels; one of them is HFO (Guerriero et al., 2013). HFO has an advantage in being cost-effective. Although the growth of harnessing renewable energies is remarkable, HFO power plants remain one of the key power sources. In the power plant, the fuel is converted to heat energy which is used to produce steam via boilers. Then, the high-pressure steam is used to rotate turbine blades through which the electricity is generated. In 2018, HFO accounted for 3 % of the world electricity production and relatively higher usage was observed in Middle-East countries (20% or even more) (BP, 2019).

(b) Natural gas

Natural gas has a production process similar to HFO. Normally, natural gas is produced by separating oil and gas while extracting energy from reservoirs. The natural gas is sent to gas power plants to produce electricity through the combustion and expansion of the gas turbine. The produced waste heat during this process can be also used to generate further electricity.
Cheap price for operation and fast building process of natural gas power plant makes this fuel attractive. In addition, they also have significant high thermodynamic efficiencies compared to other plants and it relatively emits fewer pollutants such as NO_x, SO_x, and particulate matters (PM) than coal and oil during their operation. Nonetheless, natural gas has been known as having a significant impact on climate change as producing a high level of carbon dioxide and methane. In 2018, natural gas accounts for 23.2% of global electricity production as ranked the second largest after coal (BP, 2019).

(c) Biomass

Biomass, an organic material, is a kind of renewable energy. It is often called 'photosynthesis' because it contains the energy used by the sun. Thus, the chemical energy of biomass is converted into thermal energy and released when biomass is burned in a form of liquid biofuel or biogas. There are many types of biomass such as wood and wood processing waste, crops and waste, food waste in garbage, animal manure, and human sewage (EIA, 2020a). To obtain biomass, CO_2 and flue gas are added to the pond along with nutrients and fertilizers. After that, the deposited algae are sent to an industrial vessel or chamber filter pressure for dehydration. Finally, biomass is produced by a drying process using waste heating and natural gas heating, and transferred to a biomass power plant to generate electricity (Zaimes and Khanna, 2013). It, in 2018, accounts for 2% of the world electricity production (BP, 2019).

(d) Hard coal

Hard coals are primarily obtained through mining and used as a common energy source to operate the steam turbine in power plants. The hard coal obtained through mining is transported to countries in demand. The coal-fired power plant then burns the fossil energy to produce steam that flows with tremendously high pressure to rotate the turbine so that the electricity is generated through the turbine. The steam is then cooled, condensed back into water, and returned to the boiler and the process is repeated again (TVA, 2020).

(e) Biogas

Biogas is a mixture of various gases produced by the decomposition of organic matter in the absence of oxygen. It mainly consists of methane and carbon dioxide which can be produced from raw materials such as plants, agricultural waste, municipal waste, sewage, green waste, or food waste. The process of biogas production begins with material collection and proceed with pre-treatment process, homogenization, and mixture in tanks. The material which is from this process transfers to an anaerobic tank and biogas is formed by anaerobic digestion phenomenon. This gaseous energy can be used as fuel like coal gas to produce electricity in power plants (Zafar, 2020).

(f) Lignite

Lignite, also known as brown coal, is a combustible sedimentary rock formed from naturally compressed peat. The lignite is stored in the middle of coal bunkers in the power plant. It is transported to the inside of power plants with conveyors and is crushed, dried, and powdered to dust. Then this is transferred into the combustion chamber of boilers for steam generation. The high-temperature steam is led into impellers and turn the turbine shaft to generate electricity. However, various types of emissions are released during the combustion process so that the environmental impacts of lignite are also marked high (LEAG, 2017).

(g) Coal gas

Coal gas is combustible gaseous energy obtained from coal sediment and supplied to users through pipelines. This fuel is a mixture of calorific gases such as H_2 and CH_4 which are consumed to generate electricity in power plants. To produce the coal gas, the coal in a closed tube called as 'retort' is heated in a furnace. The released gases pass through a water trap and then cooled in a condenser and a purifier to remove impurities. Then, it is stored in a gas holder as ready for use. As a conventional fossil fuel, coal gas power plants contribute to high emission levels.

(h) Peat

Peat is a buildup of partially decaying vegetation or organic matter created by their decomposition in wetlands such as swamps. Peat is consumed as domestic heating or the fuels of a boiler. Also, it is used to generate a small capacity for electricity. Peat has advantages of being used in the countries where they do not have fossil fuels, and it can develop a local economy that is able to obtain peat. However, using peat as fuel is a significant problem for the environment as producing various emissions in large quantities (Energy Institute, 2015).

(i) Nuclear

Nuclear reactor is widely used to generate steam that drives steam turbines connected to generators for electricity production. Uranium mining is the first stage to operate nuclear energy. After processing milling, the yellowcake is formed as a result of milling. The next process is to convert yellowcake to hexafluoride (UF6). Natural uranium contains about 0.7% of U-235, which is not enough for use as nuclear power plant fuel. Therefore, U-235 density is increased by an enrichment process. Lastly, this uranium is transformed to proper fuel form through a fabrication process (EIA, 2020b). Nuclear power is the electricity generated by nuclear fission. Nuclear power accounts for 10% of electricity production in the world and operates in 30 countries. (Afework et al., 2020). Despite concerns about nuclear waste, nuclear energy is attracting attention as a countermeasure against climate change as it can reduce air pollutants as much as renewable energy.

(j) Photovoltaic (PV)

Photovoltaic is the process of obtaining electricity from light or converting solar energy, the most abundant energy on the planet, into electricity. PV panels can be installed anywhere that has access to daylight and can be used to charge batteries or connect to the national grid. All PV cells consist of two or more thin semiconducting material, most of them are silicon. When sunlight strikes the silicon, electric charges are conducted by metal contacts as direct current (DC). PV systems are advantageous for their flexible design, easy and fast installation (Khodizoda, 2017). As a renewable energy, PV systems can contribute to cleaner power production.

(k) Waste

The waste-to-energy method produces heat or electricity by burning solid waste in an incinerator. The solid waste is burned at a high temperature to generate heat and steam, and the steam turns a turbine to generate electricity. Waste-to-energy is attracting attention as an effective alternative energy instead of using fossil fuels because it emits less CO_2 compared to fossil fuels. (EIA, 2020c). Applying waste-to-energy as an alternative fuel to power plants can reduce huge amounts of solid waste. In general, all solid waste should be landfilled, but burning solid waste can converts waste into electrical and/or thermal energy (Rinkesh, 2020).

(l) Geothermal

Geothermal power plants use hot water resources obtained from the earth with high-temperature hydrothermal energy supplied from dry steam wells or hot water wells (EIA, 2019). The heat originated from geothermal hot water is transferred to another liquid so that the second liquid is transformed into steam then the steam applied to generator turbine (Saveonenergy, 2019).

(m) Wind

Wind energy refers to the use of natural wind power in our environment to convert the motion of air into mechanical energy. Turbines are mainly used to generate electricity from wind power. Wind energy is also growing in importance and is impacting global electricity production. An advantage of wind power as a renewable energy is its emission-free operation. On the other hand, it is difficult to predict the accurate wind speed so that sustainable power supply would be an possible issue according to wind conditions (Campbell et al., 2020).

(n) Hydropower

Hydropower is a conversion process that generates electricity from the mechanical potential energy of flowing water. Hydroelectric power plants can generally be defined in two types: river and storage hydro power plants. The hydroelectric power plant installed along the river uses the flow of water to produce electricity, and the storage method is to move one storage tank to another using a pump. The flow of water from the pump can make electricity by rotating the turbine (ANDRITZ, 2020). Hydropower currently accounts for 16% of global electricity production. Hydropower has the advantage of producing electricity with less emissions than fossil fuels. In addition, the low cost of running dams and reservoirs allows for efficient management of these facilities (Cey et al., 2016). Although high-quality energy can be easily generated by using the mechanical energy of water, energy loss due to friction cannot be avoided when energy is transported (ECAVO, 2016).

3.1.3 Life cycle impact assessment (LCIA)

LCIA was designed to deal with quantifying the holistic environmental impacts of the electricity under various scenarios established in the previous section. This process encapsulates all the complexity associated with a prodigious number of emissions into single values which are often called environmental potentials. The marine ships are primarily operated on fossil fuels which inevitably produce marine air pollutants such as CO_2, CO, CH_4, HCl, NO_x, SO_x and NMVOC. Those emissions directly contribute to GWP, Acidification potential (AP), Eutrophication potential (EP) and Photochemical Ozone creation potential (POCP). Among various impact potentials, this paper will focus on the following four impact categories for reasons that are mostly concerned and restricted by current maritime environmental regulations:

a) GWP is the most commonly used environmental indicator. Given that the International Maritime Organization (IMO) is currently calling for a 50% reduction in GHG emissions by 2050 in the global shipping sector, the GWP will be an effective gauge to measure GHG levels for the case studies which will follow in Section 4.

b) AP is a type of pollution that can acidify soil and water. The high sulfur content of marine fuels produces SO_x emissions from engine combustion that significantly contribute to the increase in AP. Therefore, these emissions are strictly controlled by the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Regulation 14.

c) EP is an indicator to measure the degree of soil and water contamination by excess nutrients. The high levels of NO_x from engine combustion cause EP effects significantly so that IMO MARPOL Annex VI Regulation 13 has been enacted to control these emissions.

d) POCP represents near-ground high concentrations of ozone with detrimental effects on human health and plants. Another major contaminant from marine engines, NMVOC, is known to be the main culprit of POCP so its emissions are strictly limited by IMO MARPOL Annex VI Regulation 15.

In this context, the authors were convinced that these four environmental potentials should be adopted for comparison in different scenarios as they are credible indications of those maritime environmental regulations.

Fig. 8 to Fig. 11 represent lifecycle environmental impacts of the proposed 14 energy sources for electricity generation across the 36 countries. Those figures are illustrated by the proposed four environmental impact potentials, GWP, AP, EP and POCP according to the different scenarios. The LCA results described in those figures were obtained through the preliminary analysis with the GaBi LCA database (Sphera, 2020). Those results make the underlying argument raised in this paper more convincing. In particular, the comparison of those impacts of different energies clearly demystifies the holistic environmental benefits or harms of each energy. In details, the electricity production from fossil-based fuels such as hard coal, HFO, coal gas, natural gas was observed to have relatively high GWPs in all countries as shown in Fig. 8 (b), (e).

These figures are also delivering an important message that the same primary energy sources will results in different level of emissions according to the countries they have different electricity production methods and supply chains, etc. For example, Fig. 8 (a) compares the environmental impacts of biogas, biomass, and peat for electricity generation according to 36 countries. On the other hand, there are some interesting points spotted with bio-fuels - biogas and biomass - known as clean renewable energy sources. The GWPs for those fuels were estimated greater than other energy types; those environmental impacts were shown far more severe than fossil-based fuels. The environmental impacts of bio-energies are highly dependent on how they are produced as key processes for firing, flue gas cleaning and electricity generation are highly likely to produce various types of emissions in large quantities. In addition, conventional methods of biofuel production often use crops - that were originally considered to be food supply - for a different purpose. While these crops obviously help reduce emissions, this indirect land use (ILLU) implies a negative impact on the environment from a life cycle perspective as an extra process is inevitably necessary to re-growing the crops for food. In fact, the LCA results urge us to cast a doubt on whether bio-energies need to fall into green energy sources.

Although advanced methods use waste or recycling materials to produce biofuel and biomass so that those negative impacts associated with ILLU can be resolved, it should be mentioned that the analysis in this paper was conducted based on the conventional biofuel production methods only so that environmental impacts were found greatly high due to the brevity of the LCA studies on the advanced methods of biofuel productions. Contrarily, it shows that the effect of GWP can be significantly reduced regardless of the country when producing electricity using traditional renewable energy sources such as geothermal, hydro, solar and wind power that marked as relatively low GWPs. In particular, wind and hydropower are marked at their lowest levels.

It may be worth discussing nuclear power plants that are struggling to dispose of radioactive waste. The emission levels associated with nuclear power are as low as hydro and wind power. The remarkable benefits of lowering the emission level can also raise the question of whether the global trend of denuclearization is ultimately the right decision.

The environmental impacts of all energy sources are highly sensitive to the countries. In other words, while general trends are consistent across countries, one thing to note is that the GWP generated per unit of electricity production (1 kWh) varies depending on countries. European countries were observed to produce relatively lower emissions than countries in other continents such as Asia or America. Looking at Biogas, 1 kWh of electricity produces about 3.1 kg CO_2 eq. in India but 1.2 kg CO_2 eq. in Switzerland. Given this, it can be surmised that the European electricity production process is more likely to be cleaner. With coal gas, India emits 1.65 kg CO_2 eq. but Finland only emits 0.75 kg CO_2 eq per unit kWh production. The gap is higher than double, which is derived from the national or region-specific situations. LCA considers the national and regional specific technology standards of the power plants regarding efficiency, firing technology, flue-gas desulphurisation, NOx removal and de-dusting etc.

The disparity is also caused by different supply chains. For example, some countries are importing coal from Australia by shipping. Since LCA includes the emissions from the fuel supply in long distance (like waterborne transportation), the same coal power plant will make big difference between the importing countries and Australia who is a largest coal producer. Similar trends are also found with hard coal, HFO Lignite, and waste too as the max, min gaps are more than significant. In general, the non-fossil energy sources have relatively lower gaps between the maximum, minimum and mean values across the countries. However, waste has a quite irregular and wide range from as small as zero to as high as 1.0 kg CO_2 eq. /kWh.

Results obtained from other local environmental impacts of AP, EP and POCP reveal similar trends as well. Those values are much smaller than the GWP though. Fossil-based fuels (hard coal and HFO) also have the highest impact levels, whereas coal gas and natural gas have relatively lower impacts than those of hard coal and HFO. Renewable energy is relatively low. On the AP side (see Fig. 9), we can find notable spots in geothermal energy sources. Considering that six out of 36 countries use geothermal energy, most of them generate high APs. This trend is very different from other influences. Germany, for example, uses geothermal energy to generate electricity to produce 0.009 kg SO_2 eq./kWh, which is very similar to light biogas in the United States. Hydro, nuclear, solar and wind power are relatively small.

For EP (see Fig. 10), biogas and biomass were found to have higher adverse effects on the environment as their functional units are relatively higher than other energy sources; even far greater than HFO, for renewable energies such as photovoltaic or wind power. By contrast, wind power, geothermal and hydropower were revealed to have the least effects on EP. The overall EP trend is largely in the same line with the other potentials. An interesting point is that the impact of coal gas was sensitive to nations. For example, the functional unit for Netherlands is 0.0003 kg/kWh but it climbs up to 0.0012 kg/kWh (about 4 times) for India. The distinction of these impacts among the nations will be further discussed with the following figures. Another interesting point was observed with nuclear power which was found to have a relatively higher effect on EP than geothermal. This trend is dissimilar with GWP and AP where geothermal was remarkably high when compared to nuclear power.

As shown in Fig. 11, the general trend of POCP is moderately similar to that of EP. One different point can be found that biomass has a higher impact on POCP than biogas. In fact, the biogas was revealed a high attribute to EP. The other groups of energies show similar observation although the total quantify of emissions are relatively lower than other potentials. Again, wind power, geothermal, and hydropower were confirmed with the least environmental effect.

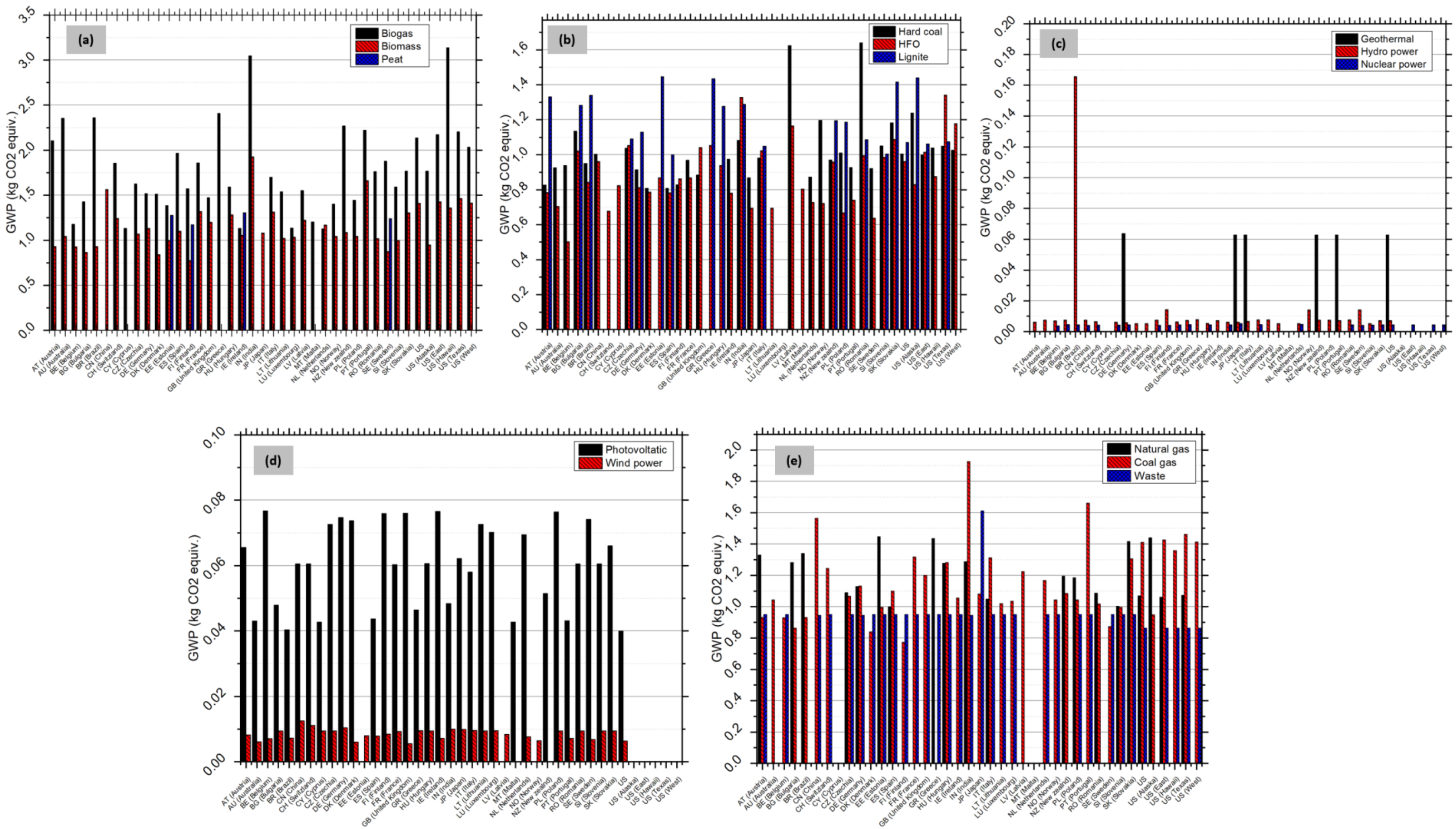


Fig. 8. Various GWPs from electricity production according to countries and energy sources: (a)Biogas, Biomass, Peat; (b) Hard coal, HFO, Lignite; (c) Geothermal, Hydropower, Nuclear power; (d) Photovoltaic; Wind power; (e) Natural gas, Coal gas, Waste.

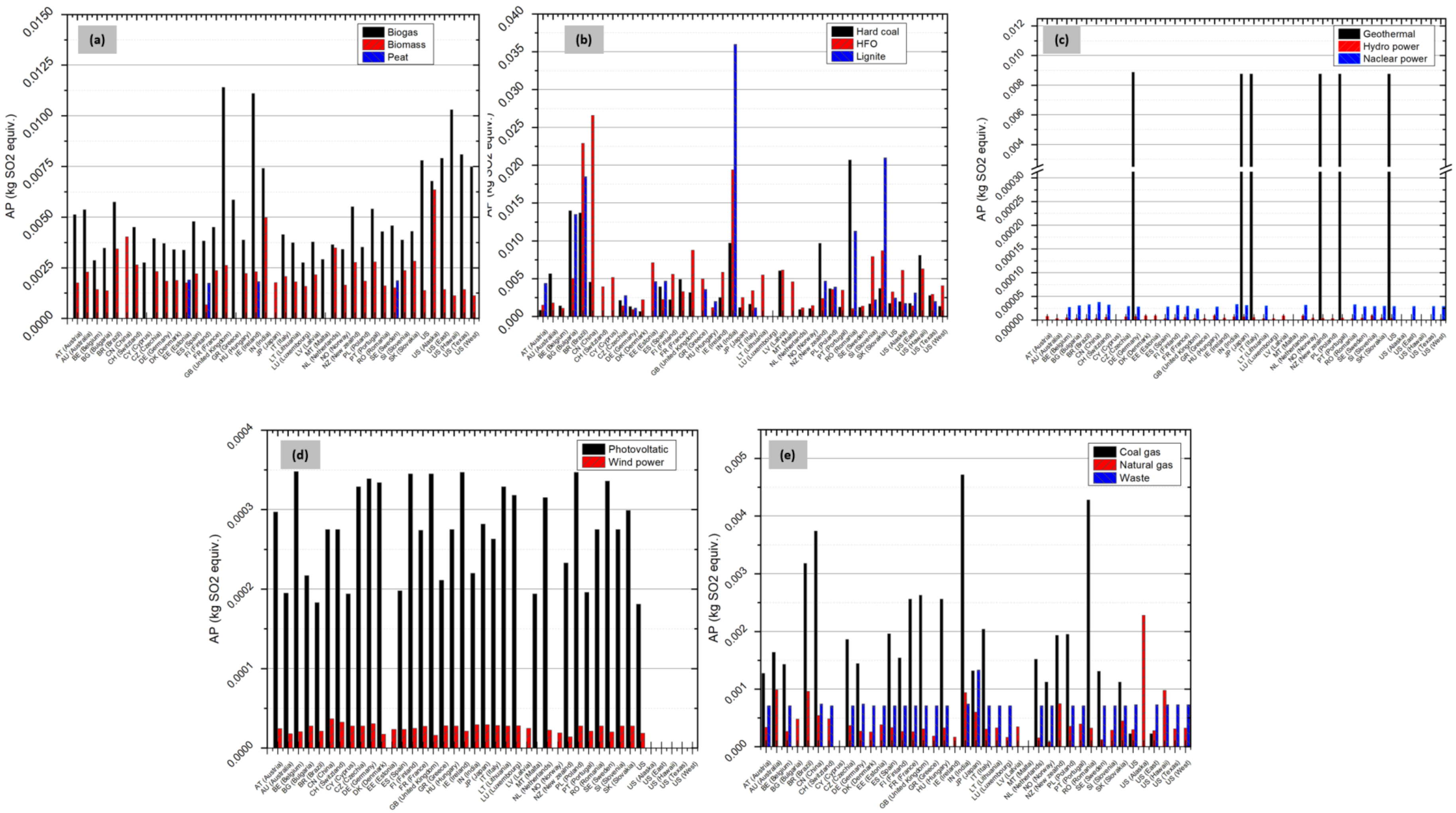


Fig. 9. Various APs from electricity production according to countries and energy sources: (a)Biogas, Biomass, Peat; (b) Hard coal, HFO, Lignite; (c) Geothermal, Hydropower, Nuclear power; (d) Photovoltaic; Wind power; (e) Natural gas, Coal gas, Waste.

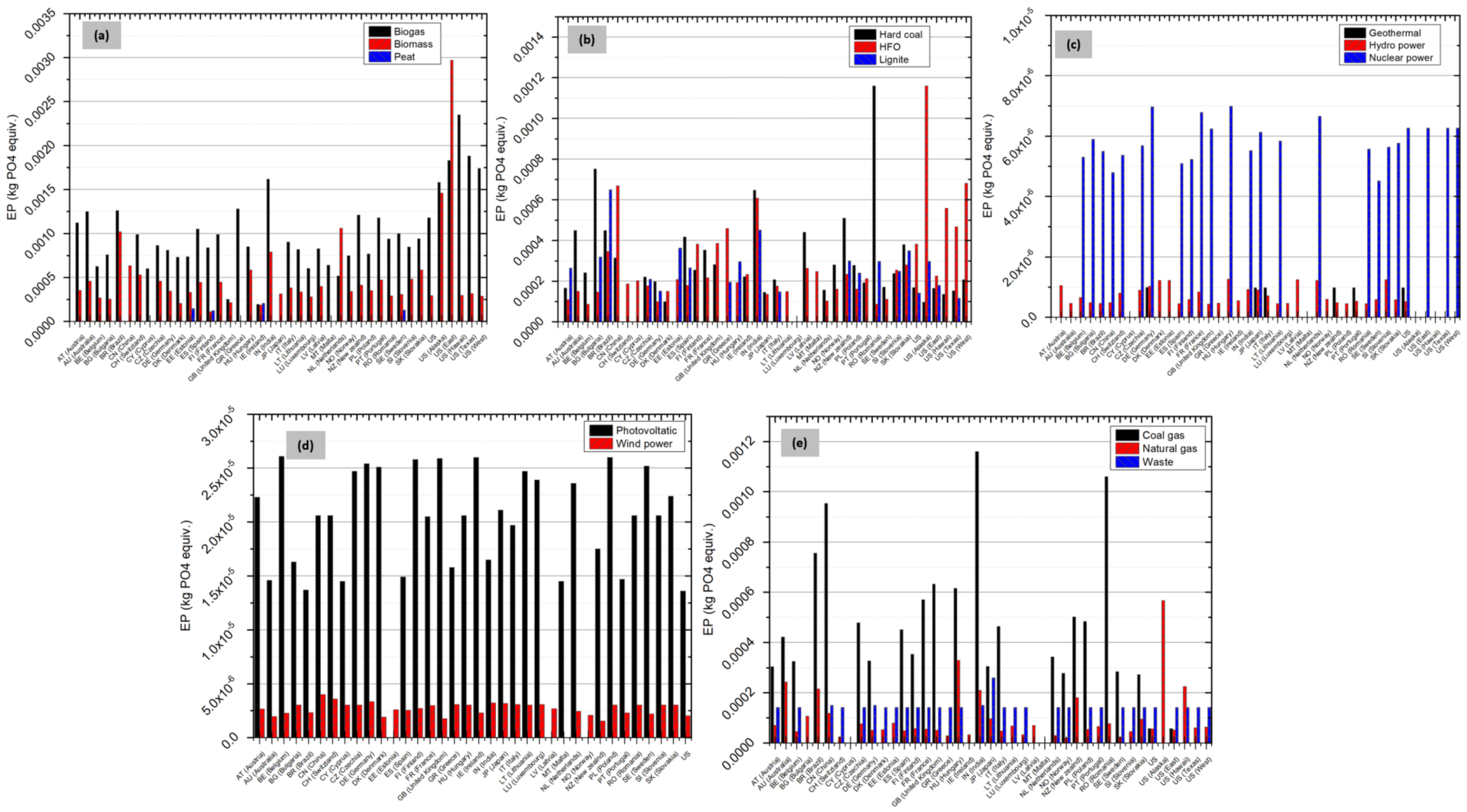


Fig. 10. Various EPs from electricity production according to countries and energy sources: (a)Biogas, Biomass, Peat; (b) Hard coal, HFO, Lignite; (c) Geothermal, Hydropower, Nuclear power; (d) Photovoltaic; Wind power; (e) Natural gas, Coal gas, Waste.

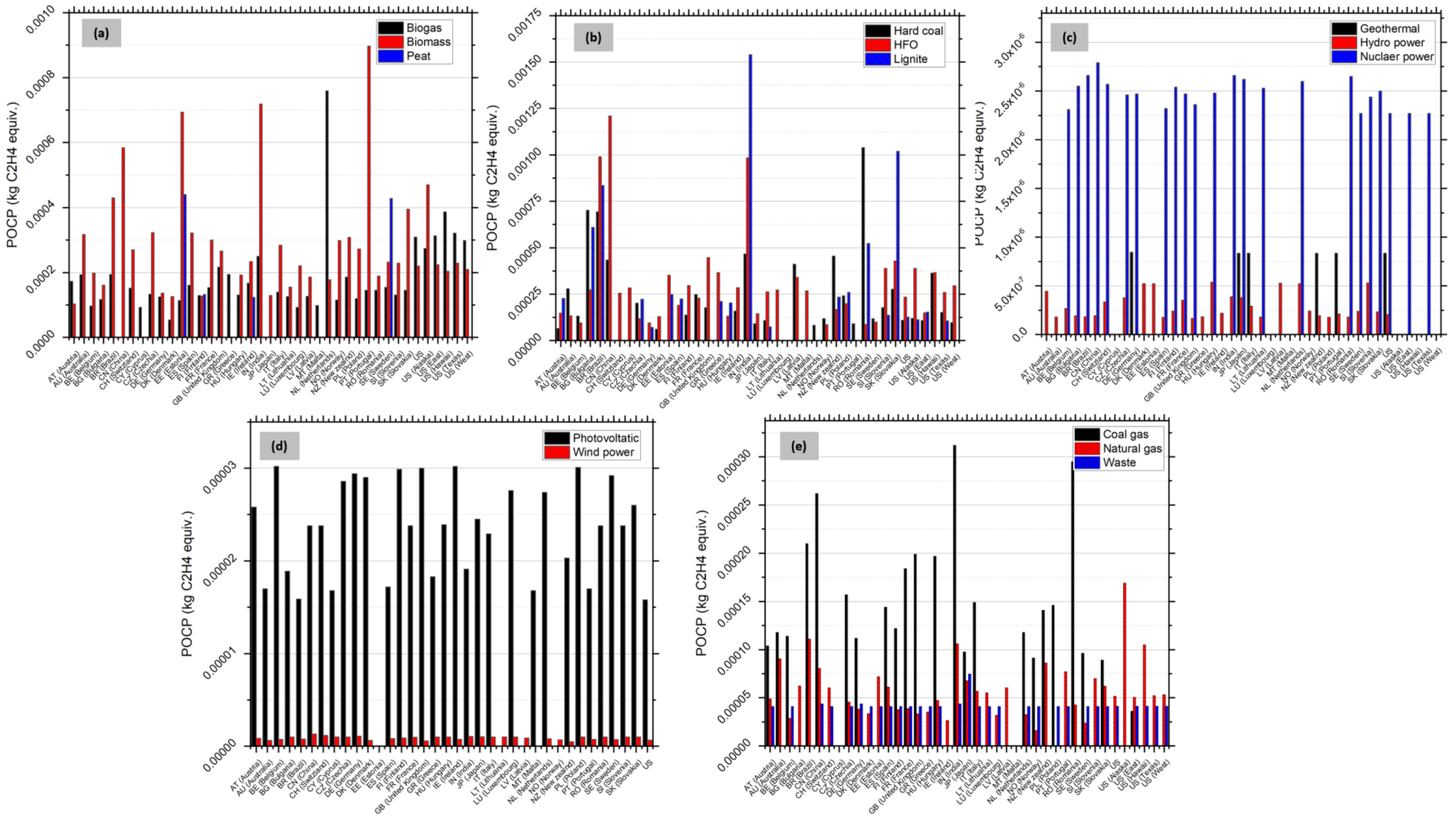


Fig. 11. Various POCPs from electricity production according to countries and energy sources: (a)Biogas, Biomass, Peat; (b) Hard coal, HFO, Lignite; (c) Geothermal, Hydropower, Nuclear power; (d) Photovoltaic; Wind power; (e) Natural gas, Coal gas, Waste.

The sizable differences in environmental impacts across countries are more explicitly revealed in Fig. 12 which displays the distribution of the environmental impacts for the 14 energy sources across the total of 36 countries, whereas those impacts expressed in Fig. 12 were trimmed into Table 1 that presents the maximum, minimum and average values only according to the types of energies and the countries. In other words, this table represents ‘worst’ and ‘best’ and ‘average’ cases at different fuels to show their gaps numerically.

This figure and table also stress on that using clean energy is not the only issue to be considered, countries producing those energies are also highly important for optimal use of the energy. Similar trends are also found in AP, EP and POCP as well. Those graphs indicate the sensitivity of the production methods and supply chain associated with each country.

In summary, the results of biogas, biomass, peat, and lignite were found much greater than other fuel types in terms of emission levels. However, renewable energy sources such as geothermal, hydro, solar and wind power mostly were revealed with lower emission levels. The difference between the average values of biogas (confirmed the highest) and renewable energy (confirmed the lowest) were found as much as 1.7 CO_2 eq./kWh. The results of the analysis generally show that GWPs are higher than other local impacts, while POCP values are the lowest. In addition, the average amount of emissions for fuels other than biofuels, nuclear and renewable energy is about 1.0kg CO_2 eq./kwh. Similar trends can be found in the local pollutants as well. Conversely, POCP is lower than other types of emissions. Peat represents the highest emissions and is distributed over the widest range of values. The average emission value for each fuel type is less than 0.0003kg C_2H_4 eq., indicating that the POCP value is unusually high because certain countries have more outliers compared to other pollution potential graphs. Also, in this graph, renewable energies typically emit much less.

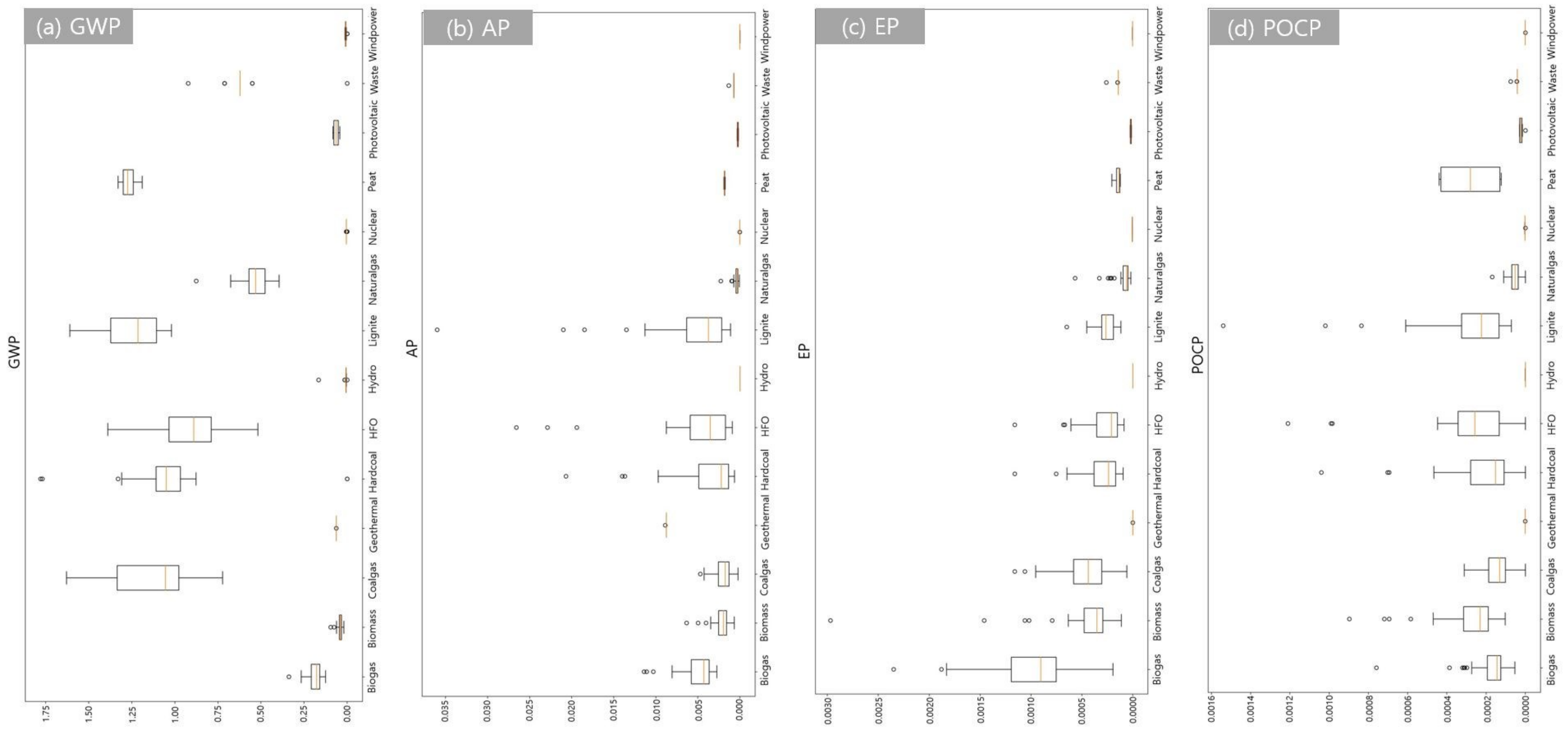


Fig. 12. Environmental impact factor for various energy sources with geographical differences.

Table 1

Electricity from land pollution potentials (Unit: kg / 1 kWh electricity production).

Type of pollutant	Pollution potentials												
	GWP (kg CO_2 equiv.)			AP (kg SO_2 equiv.)			EP (kg PO4 equiv.)			PCOP (kg C2H4 equiv.)			No. of countries
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	
Biogas	3.38.E-01	1.26.E-01	1.89.E-01	1.14.E-02	2.75.E-03	5.16.E-03	2.35.E-03	1.94.E-04	1.01.E-03	7.59.E-04	5.37.E-05	1.85.E-04	34
Biomass	9.53.E-02	1.90.E-02	4.17.E-02	6.35.E-03	6.82.E-04	2.24.E-03	2.97.E-03	1.12.E-04	5.07.E-04	8.97.E-04	1.03.E-04	2.90.E-04	33
Coal gas	1.63.E+00	7.24.E-01	1.15.E+00	4.72.E-03	2.25.E-04	1.98.E-03	1.16.E-03	5.78.E-05	4.77.E-04	3.12.E-04	2.45.E-17	1.46.E-04	23
Geothermal	6.39.E-02	6.31.E-02	6.32.E-02	8.88.E-03	8.76.E-03	8.78.E-03	9.89.E-07	9.75.E-07	9.77.E-07	8.46.E-07	8.34.E-07	8.36.E-07	6
Hard coal	1.78.E+00	1.09.E-04	1.04.E+00	2.07.E-02	6.65.E-04	4.28.E-03	1.16.E-03	9.65.E-05	3.08.E-04	1.04.E-03	5.55.E-17	2.40.E-04	28
HFO	1.39.E+00	5.18.E-01	9.18.E-01	2.66.E-02	9.28.E-04	5.22.E-03	1.16.E-03	8.64.E-05	2.81.E-04	1.21.E-03	5.12.E-17	2.86.E-04	35
Hydro power	1.66.E-01	1.78.E-07	1.18.E-02	9.52.E-06	3.42.E-06	5.67.E-06	1.26.E-06	4.31.E-07	7.35.E-07	5.39.E-07	9.47.E-18	2.87.E-07	34
Lignite	1.61.E+00	1.02.E+00	1.26.E+00	3.60.E-02	1.12.E-03	7.24.E-03	6.49.E-04	1.16.E-04	2.74.E-04	1.54.E-03	7.18.E-05	3.57.E-04	17
Natural gas	8.76.E-01	3.96.E-01	5.36.E-01	2.28.E-03	8.36.E-05	4.43.E-04	5.67.E-04	2.04.E-05	9.84.E-05	1.69.E-04	1.54.E-17	5.71.E-05	34
Nuclear	5.68.E-03	2.60.E-06	4.53.E-03	3.81.E-05	2.38.E-05	3.02.E-05	6.99.E-06	4.52.E-06	5.86.E-06	2.79.E-06	1.30.E-17	2.38.E-06	21
Peat	1.33.E+00	1.19.E+00	1.27.E+00	1.91.E-03	1.75.E-03	1.84.E-03	2.06.E-04	1.23.E-04	1.51.E-04	4.40.E-04	1.23.E-04	2.81.E-04	4
Photovoltaic	8.28.E-02	4.31.E-02	6.52.E-02	3.48.E-04	1.81.E-04	2.74.E-04	2.61.E-05	1.36.E-05	2.05.E-05	3.02.E-05	3.52.E-13	2.29.E-05	33
Waste	9.23.E-01	4.11.E-05	6.19.E-01	1.33.E-03	7.10.E-04	7.37.E-04	2.60.E-04	1.42.E-04	1.47.E-04	7.46.E-05	4.11.E-05	4.25.E-05	27
Wind power	1.33.E-02	7.53.E-07	8.24.E-03	3.68.E-05	1.41.E-05	2.50.E-05	4.01.E-06	1.54.E-06	2.73.E-06	1.31.E-06	9.19.E-15	8.68.E-07	35

Through the analysis, the following points could be corroborated.

1) From a lifecycle perspective, each energy source may produce greater environment harms than actual measurements and/or estimates indicate in a single life stage such as the power generation or onboard. Even energies known as zero-emission fuels also contribute to producing emissions to some extent. To fully protect the planet, estimates of the holistic impacts of energy sources cannot be ignored.

2) Lifecycle environmental impacts show that the different type of energies have different levels of emissions for different potentials. It is also true that while renewable resources are overall superior to fossil-based fuels, the impact of these energy sources is not negligible. Geothermal, for example, has a very large impact on APs.

3) Even if the same energy source is used for power generation, it is sensitive to location. This is because LCA considers subsequent emissions related to production methods, supply chains, etc. This discrepancy guides us to recognize that best policies for energy use and environmental protection may differ from country to country.

4) From the viewpoint of life cycle evaluation, biogas generates a small amount of emission during the use stage, but it is not suitable as an alternative fuel because it generates a large amount of emission to GWP and EP during the production process.

5) When using renewable energies, such as geothermal, hydropower, photovoltaic and wind power, the emissions claimed to generate electricity are much lower. However, weather, and geographical factors play a large role in harnessing those renewable energies, making it difficult to commercialize it easily.

In fact, these results offer an insight into what the marine industry needs to comprehend when formulating appropriate energy policies for global shipping.

4 Case study (Steps 2 and 3)

Step 2 was organized to implement the LCA models of electricity production developed in Step 1 for the marine application. In fact, this task is to demystify the holistic benefits/harms of the battery powered ships compared to conventional diesel ships as well as to determine the best scenarios to maximize their benefits, if any, across nations.

4.1 Step 2-1: Scenario development

The case studies begin with the nearest cases with the short route ferries engaged in the west-Scotland coastal areas. Total 24 vessels data were collected; three of them are actual battery-powered ships. Given that this service is operated by multiple operators, this research was collaborated with a fleet of ships from Caledonian MacBrayne, a major operator serving more than 20 destinations as shown in Fig. 13 and Table 2. Their operation begins every morning to evening so that it is a perfect fit for the battery operation and overnight charge.

The analysis assumed that the other vessels would also operate on the same concept as the original three battery-powered vessels, but the battery capacity was determined by the propulsion required for each vessel. For example, a ferry with a 500-kW diesel engine was assumed to have been converted to a 500-kW battery pack.

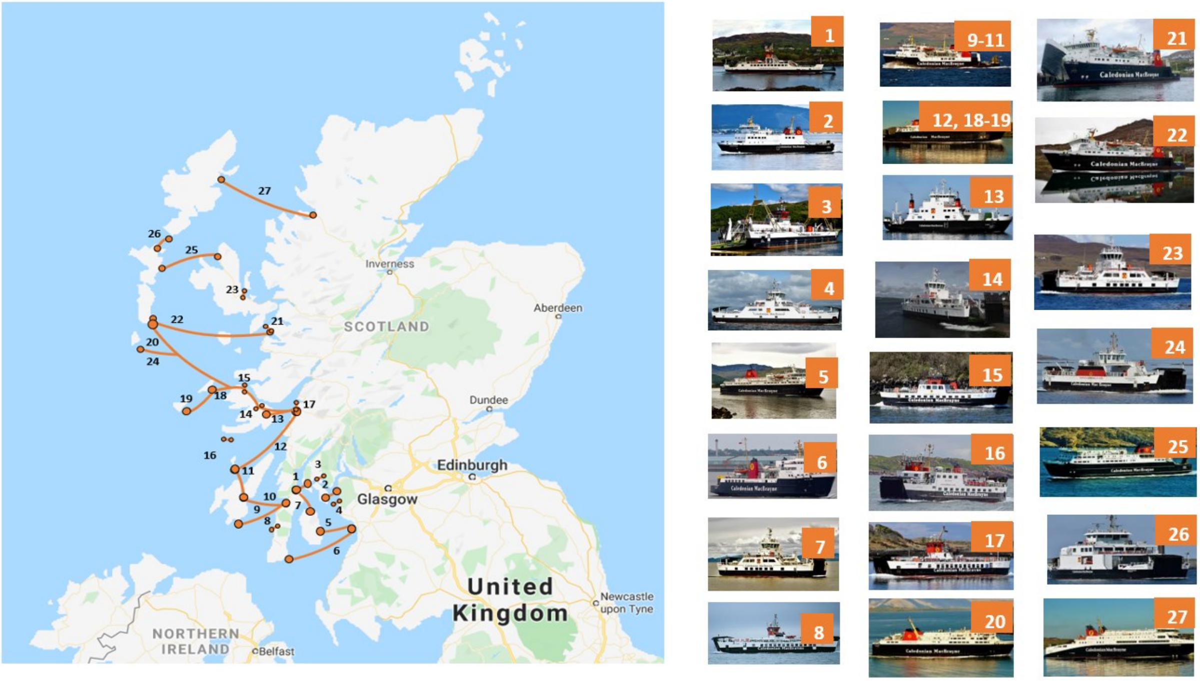


Fig. 13. Service routes for West Scotland short route ferries (CMAL, 2022)

Table 2

Servicer information for West Scotland short route ferries (CMAL, 2022)

Service route	Regular vessel(s)	In service	Mainland or inner port	Island or outer port	Voyage Time (hours)	Daily trip	No. of engines	Propulsion power (kW)	Propulsion type (Hybrid/DE/DM)
1	Isle of Cumbrae	1977	Portavadie, Cowal	Tarbert, Kintyre Peninsula	0.42	19	2	220	DM: diesel mechanic
2	Argyle & Bute	2007	Wemyss Bay, Inverclyde	Rothesay, Isle of Bute	0.58	13	1	2,696	DE: diesel electric
3	Loch Dunvegan	1991	Colintraive, Cowal	Rhubodach, Northern Bute	0.08	96	1	659	DE
4	Loch Shira	2007	Largs, North Ayrshire	Cumbrae Slip, Isle of Cumbrae	0.17	48	2	540	DE
5	Caledonian Isles	1983	Ardrossan, North Ayrshire	Brodick, Isle of Arran	0.92	8	2	1,749	DE
6	Isle of Arran	1983	Ardrossan	Campbeltown, Kintyre	2.67	3	2	1,749	DE
7	Catriona	2015	Tarbert, Kintyre Peninsula	Lochranza, Isle of Arran	1.90	4	3	330	Hybrid: battery with DE
8	Loch Ranza	1987	Tayinloan, Western Kintyre	Ardminish, Isle of Gigha	0.33	24	2	274	DE
9	Hebridean Isles	1985	Kennacraig, Western Kintyre	Port Ellen, Southern Islay	2.33	3	2	1,749	DE
10			Kennacraig	Port Askaig, Eastern Islay	2.08	3	2	1,749	DE
11			Port Askaig	Scalasaig, Isle of Colonsay	1.17	6	2	1,749	DE
12	Clansman	1998	Oban	Scalasaig, Colonsay	2.33	3	2	3,893	DE
13	Coruisk	2003	Oban	Craignure, Isle of Mull	0.77	10	2	1,156	DE
14	Lochinvar	2013	Lochaline, Morvern Peninsula	Fishnish, Mull	0.25	32	3	330	Hybrid
15	Loch Tarbert	1992	Kilchoan, Ardnamurchan Peninsula	Tobermory, Mull	0.58	13	1	491	DE
16	Loch Buie	1992	Fionnphort, Ross of Mull	Iona	0.17	48	1	491	DE
17	Loch Striven	1986	Oban	Achnacroish, Isle of Lismore	0.83	9	2	274	DE
18	Clansman	1998	Oban	Arinagour, Isle of Coll	2.92	2	2	3,893	DE
19			Oban	Scarinish, Isle of Tiree	3.33	2	2	3,893	DE
20	Isle of Lewis	1993	Oban	Castlebay, Isle of Barra	5.00	1	2	3,311	DE
21	Lord of the Isles & Loch Fyne	1989	Mallaig	Armadale, Sleat Peninsula, Skye	0.42	19	2	2,190	DE
22	Lord of the Isles	1989	Mallaig	Lochboisdale, South Uist	3.25	2	2	2,190	DE
23	Hallaig	2011	Sconser, Skye	Raasay	0.25	32	3	330	Hybrid
24	Loch Alainn	1997	Ardmhor (Barra)	Isle of Eriskay	0.67	12	2	491	DE
25	Hebrides	2000	Uig, Skye	Lochmaddy, North Uist	1.75	4	2	3,893	DE
26	Loch Portain	2003	Leverburgh, Harris	Isle of Berneray	1.00	8	4	482	DE
27	Loch Seaforth	2015	Ullapool, Wester Ross	Stornoway, Lewis	2.75	2	3	287	DE

4.2 Step 2-2: Hybrid system modelling for vessels

Fig. 14 shows the concept of the three different propulsion systems which describe the propulsion types of each case ship. Fig. 14 (b) describes a diesel electric (DE) propulsion for which the electricity produced from diesel generators is supplied to run the motor systems. Marine diesel oil is the primary fuel that runs generator engines. For Fig. 14 (a), the hybrid concept is an advanced design of (b) by adding battery system to the electric propulsion systems. Thus, it can run on electricity stored in the battery packs which are charged overnight. As for Fig. 14 (c), the concept is the diesel mechanical (DM) propulsion where the diesel engines are directly connected to the propellers.

The big difference of (a) hybrid from (b) DE, (c) DM is that hybrid ships do not produce any emission during service on condition that they are entirely operated on batteries as the electric vehicles do not produce exhaust gases on the road. In contrast, ships with DE and DM systems generate huge amounts of emissions by internal combustion engines that burn fossil fuels. However, the fundamental question lies on this paper is that battery-powered ships are plugged in with electricity from the shore. As discussed earlier in Ch. 1, to produce electricity, in-land power plants possibly produce a prodigious amount of emissions so that it is conceivable that the cleaner shipping may transmit the emission burning on the shore side rather than reducing their emission levels entirely.

To clearly obtain the inspiration on whether battery propulsion prevails the diesel electric propulsion overall, the case study conducts the comparative analysis between hybrid (a) and DE propulsion (b) in terms of holistic environmental impacts. Regarding the hybrid concept, for convenience to compare the difference in environmental performances between diesel and battery operations, this paper assumes that the battery operation is only used in case of the hybrid concept so that those ships can be regarded as full battery-powered ships. The batteries are fully charged overnight at port via the onshore electricity grid. In fact, DM was not considered as there was no significant difference from the option of DE in terms of the environmental impact of diesel fuel.

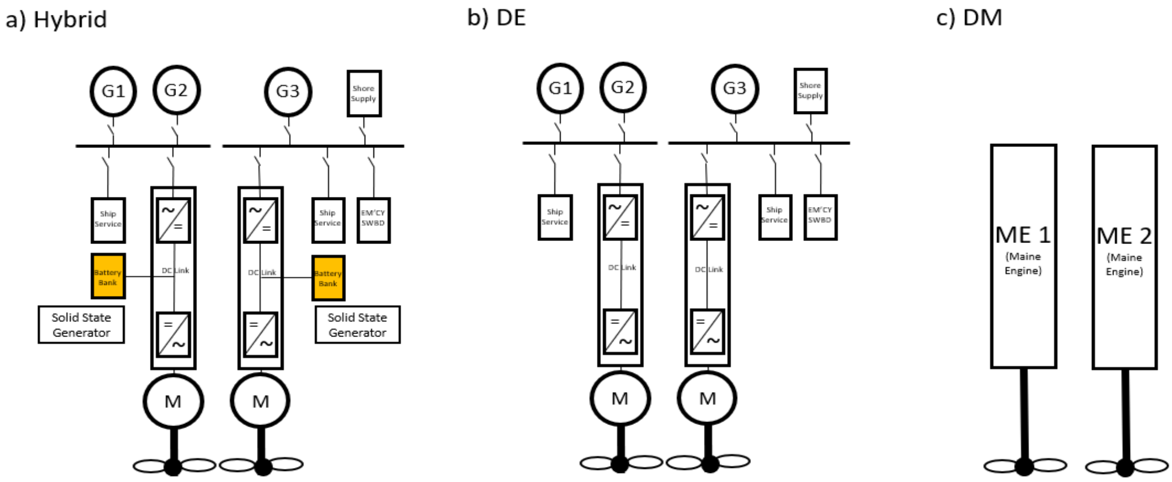


Fig. 14. Ship propulsion systems (Hybrid vs DE vs DM).

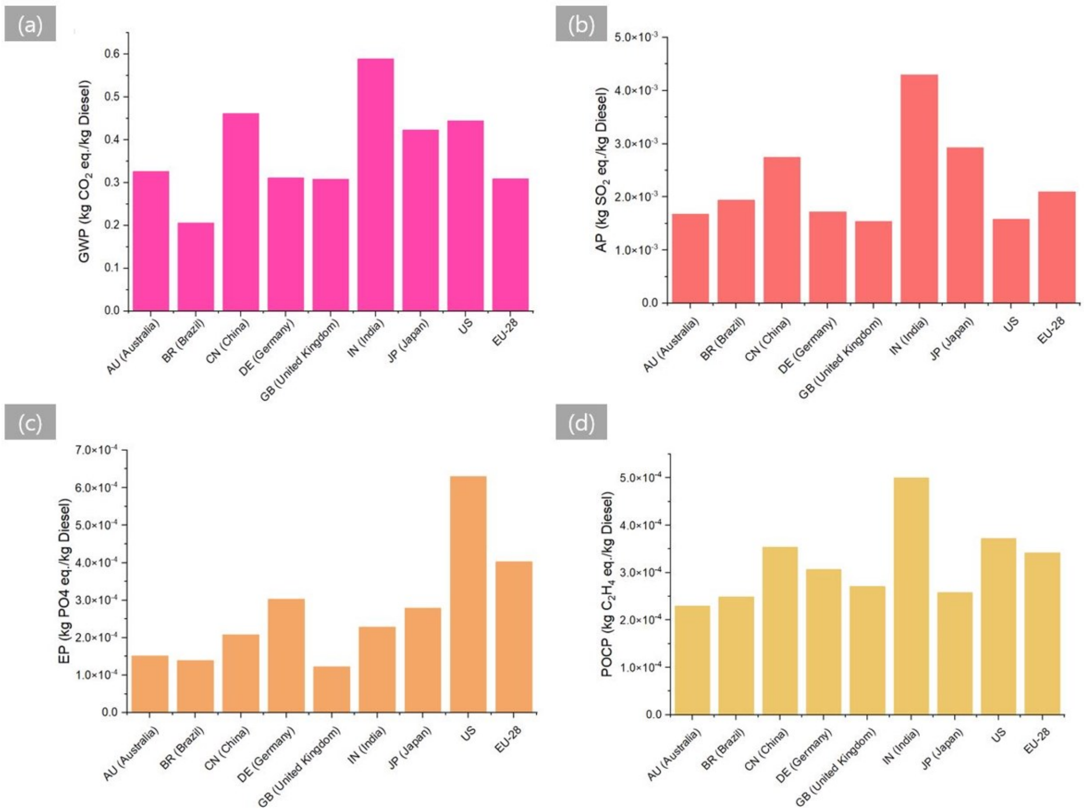


Fig. 15. Comparison in lifecycle environmental impacts of marine diesel oils vs nations (Data was extracted from GaBi Database (Sphera, 2020)).

Fig. 15 shows the LCIA results of marine diesel oils (MDO) according to several nations. It was observed that the gaps in environmental impacts according to the nations was relatively smaller than those of the electricity generation. These data are used as the reference lines to compare between the diesel and the electric propulsion throughout Case studies.

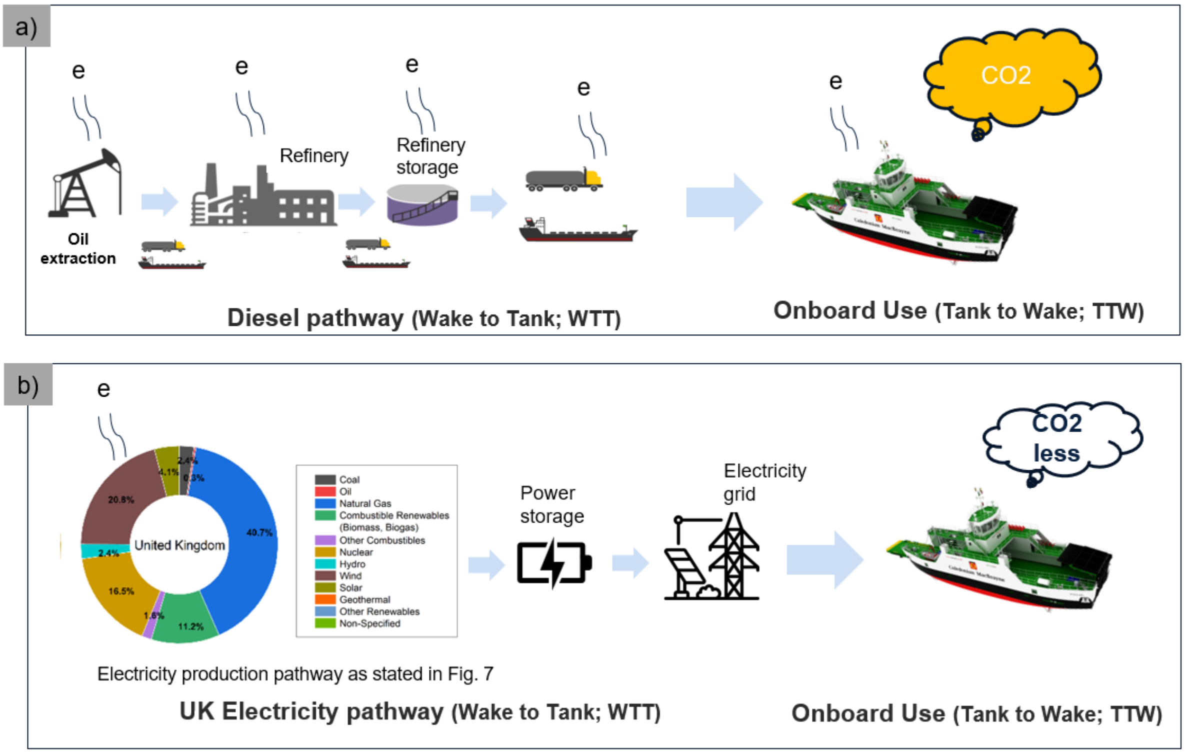


Fig. 16. Diesel pathway vs UK electricity lifecycle pathway.

Fig. 16 shows the lifecycle pathways for diesel and battery-powered ships and each life stage is subject to emissions. For diesel pathway, WTT emissions are directly referred to the LCIA results of UK diesel oil as given in Fig. 15 and the TTW emissions are calculated based on Table 3.

Table 3 Diesel engine emission factors (with MDO) (Jeong et al., 2018b)

Engine emission	Fuel-based factor (tonnes/fuel-ton)
NO_x	0.057
CO	0.0074
CH_4	0.0024

CO_2	3.17
SO_x	0.002 (= 20 × (0.1) %S content
PM	0.00095

For UK electricity pathway, WTT emissions are directly borrowed from the LCIA results in Ch. 3.1.3 and TTW emissions are negligible, provided that electric-powered operations lead to emission-free voyages.

4.3 Step 3: Case study

Through the series of case studies, the case ships with battery operation were compared to the same fleets under diesel operations. It was observed to confirm whether the electric propulsion would be excellent in terms of the environmental impacts, compared to diesel ships in both UK and other nations.

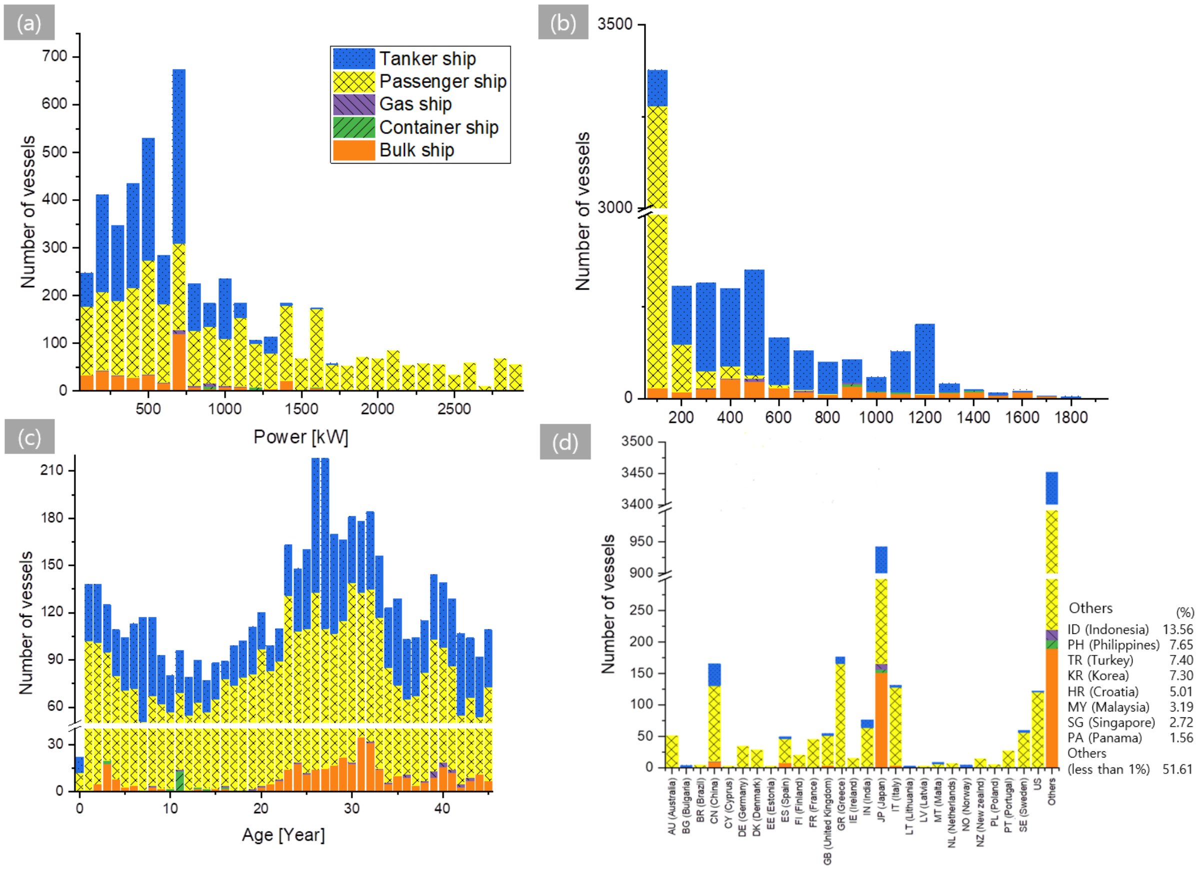


Fig. 17. General information on ships applied to sensitivity LCA analysis; the raw ship data was collected (*by curtesy of Lloyds Register*).

Since the battery technology has low energy density so that it is not suitable for large ocean-going vessels as their propulsion energy sources. As such, this paper has established a ship boundary line of 1,800 DWT or less and of five representative merchant ship types: tankers, containers, passenger ships, gas ships and bulk carriers. So, this paper obtained the data from those ships in these categories from Lloyd's Register Ship Database. It was found that about 5,500 marine vessels under those categories are presently registered with international registration numbers and presently engaged in their services. Applying the same concept of the battery system to these vessels, this paper performed the LCA sensitivity analyses in three different cases.

- Case 1: with the 24 UK short-sea ferries (described in Ch. 3.2), a comparative analysis was proposed to estimate the impacts if all the vessels are operated by diesel engines in comparison to the same vessels would be operated only by batteries charged from the UK power grids. It was also compared with the same case ships connected to Japan' power grid which has a high reliance on coal and fossil fuels in order to identify the level of gaps associated with different nations briefly.

- Case 2: world fleets (all world ships internationally registered with 1,800 DWT or less in Fig. 17) applied to the electric grid of 31 nations[4] among 36 countries analyzed in Ch 3.1. The rest five continental countries of Austria, Switzerland, Czechia, Luxembourg, Slovakia were placed out of analysis as their business cases would be far from short-sea shipping. Regarding Fig. 17 (d), the countries fell into 'others' categories are not included in LCIA studies as their LCIA for electricity production was not obtained in Ch. 3 for the simple reasons that their emission data was not accessible.

- Case 3: it was assumed that the world fleets are operated by their flag state and use the flag state's electric grid. About 2,050 ships were flagged by 27 nations among the 31 nations that were studied in Cases 2 as shown in Fig. 17 (d). The four countries of Belgium, Hungary, Romania, and Slovenia were not considered as they do not have ships registered under their flagships. Again, the ships in 'others' categories in Fig. 17 (d) are not included in the Case 3 study as their LCA data are not available for this study.

4.3.1 Case 1: the UK fleets applied to power grids of 31 nations.

[4] AU (Australia), BE (Belgium), BG (Bulgaria), BR (Brazil), CN (China), CY (Cyprus), DE (Germany), DK (Denmark), EE (Estonia), ES (Spain), FI (Finland), FR (France), GB (United Kingdom), GR (Greece), HU (Hungary), IE (Ireland), IN (India), JP (Japan), IT (Italy), LT (Lithuania), LV (Latvia), MT (Malta), NL (Netherlands), NO (Norway), NZ (New Zealand), PL (Poland), PT (Portugal), RO (Romania), SE (Sweden), SI (Slovenia), US

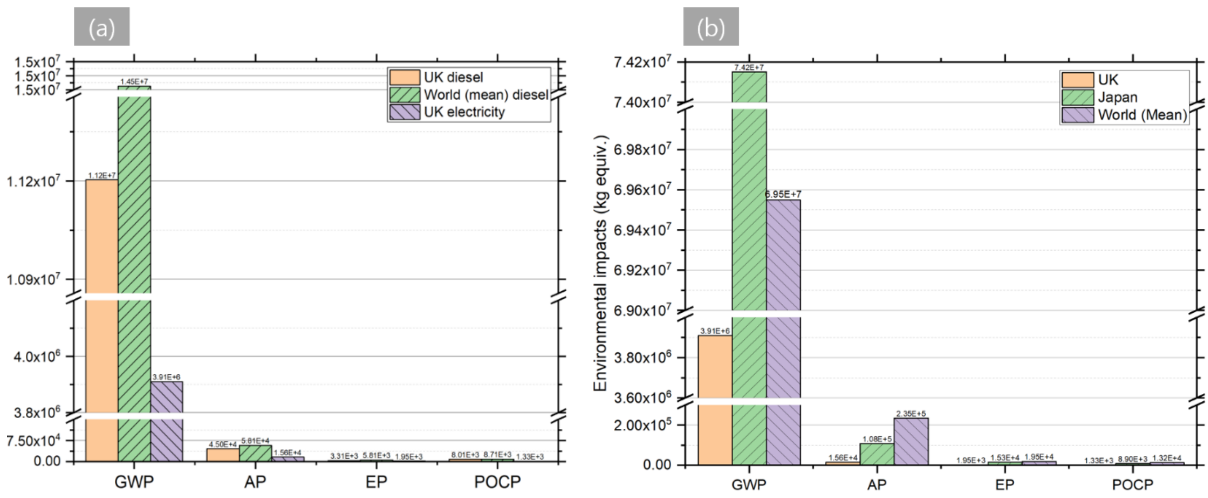


Fig. 18. Results of comparative analysis between hybrid and diesel ships.

Fig. 18 shows the LCA results of the 24 case ships with the amount of emissions from annual operation in several scenarios. Fig. 18 (a), where the case ships with hybrid concepts were compared to the same fleets under diesel operations, clearly shows that the battery electric propulsion would be excellent in terms of the environmental impacts, compared to diesel ships in both UK and world (mean) scenarios. However, the question remains that the impact of battery use on the environment is far from the zero emissions the global maritime industry is ultimately trying to achieve. More interesting results were found with Fig. 18 (b) in the comparison in the environmental impacts pertinent to the electric grids among the UK, Japan and the world (mean). Assuming that the same ship was dispatched to the coastal area of Japan, and on the same principle, charging electricity from the national grid overnight, the results are turned out surprisingly different; we can clearly see that running batteries in different regions can significantly increase the environmental impact, which is far greater than diesel operation in the UK.

This comparative analysis recurs the fundamental question of this research; whether hybrid ships will be ultimately the best solution for maritime environmental protection. The answer should be “no” as it is highly sensitive to the locations where the hybrid ships are in service. In fact, these findings go off the alarm to the public who have had false confidence with the performance of the hybrid ships.

4.3.2 Case 2: the world fleets (see Fig. 17) applied to power grids of the 31 nations.

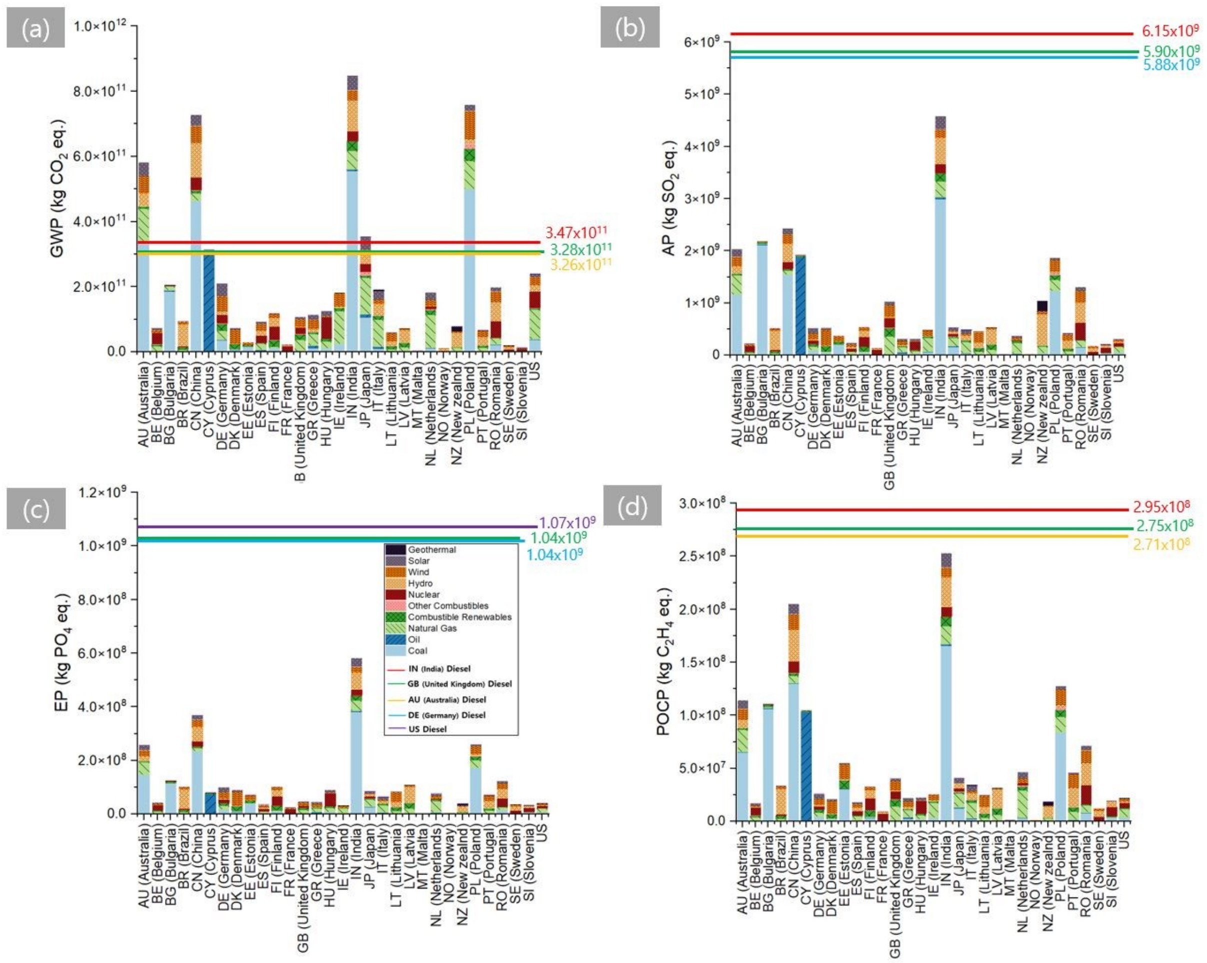


Fig. 19. Comparison in environmental impacts of world fleets according to different national power grids.

Readers may be not completely convinced of the results obtained from Case 1 in the previous section with a simple reason that the number of case ships have been oversimplified, making it hardly possible to explain the general observation of the world fleets. In response, all the vessels (about 5,500 ships) featured in Fig. 17 were assumed to be operated at the subject countries in Case 2. As the number of vessels in the analysis rises, the total emission levels are followed to increase. The overall trends are, however, identical to Case 1 (as illustrated in **Error! Reference source not found.**). It is simply because the analysis was scale-up with the significant increment in the case ships' number which is a key parameter to contribute to the emission levels.

The LCA results can be summarized as a “functional unit” equivalent to “the amount of environmental impact to produce 1 kWh of electricity”. These numbers encapsulate all information into a single value. Anyone can borrow these figures for research, making LCA results much more accessible. Table 4 shows each functional unit of different countries according to environmental impacts which are GWP, AP, EP, and POCP. As can be seen, the energy ratio and functional unit of each country remain the same so that the general trends remain unchanged. To be specific, as in Case 1, the most noticeable is the four countries such as India, Poland, China, and Australia have the greatest environmental impacts in the GWP, AP, EP and POCP. The results of Case 2 show almost the same trends as Case 1. However, the volume difference could be 200 to 250 times more than that.

When the diesel ships were operated, it would emit 3.28×10^{11} kg CO_2 Eq., 5.90×10^{9} kg SO_2 Eq., 1.04×10^{9} kg PO_4 Eq., and 2.75×10^{8} kg C_2H_4 Eq. Analysis results of AP, EP and POCP explain that overall battery ships are much greener than diesel ships, but some countries such as India, Poland, China, and Australia are not in terms of GWP. Therefore, findings from Case 2 also confirm that the way a country produces electricity has a substantial impact on the environment.

Table 4 Functional units of each country according to environmental impacts.

	GWP [kg CO_2 Eq./kWh]	AP [kg SO_2 Eq./kWh]	EP [kg PO_4 Eq./kWh]	POCP [kg C_2H_4 Eq./kWh]
AU (Australia)	1.28E+00	4.48E-03	5.67E-04	2.52E-04
BE (Belgium)	1.62E-01	4.81E-04	9.29E-05	3.69E-05
BG (Bulgaria)	4.54E-01	4.83E-03	2.73E-04	2.45E-04
BR (Brazil)	2.07E-01	1.13E-03	2.24E-04	7.40E-05
CN (China)	1.61E+00	5.38E-03	8.19E-04	4.54E-04
CY (Cyprus)	6.94E-01	4.25E-03	1.76E-04	2.32E-04
DE (Germany)	4.64E-01	1.14E-03	2.19E-04	5.74E-05
DK (Denmark)	1.59E-01	1.14E-03	1.97E-04	4.55E-05
EE (Estonia)	6.36E-02	8.13E-04	1.57E-04	1.21E-04
ES (Spain)	2.03E-01	5.05E-04	7.68E-05	3.92E-05
FI (Finland)	2.60E-01	1.17E-03	2.23E-04	7.23E-05
FR (France)	4.77E-02	2.99E-04	5.20E-05	2.04E-05
GB (United Kingdom)	2.36E-01	2.26E-03	9.99E-05	8.92E-05
GR (Greece)	2.49E-01	6.88E-04	9.63E-05	4.77E-05
HU (Hungary)	2.76E-01	6.77E-04	1.97E-04	4.91E-05
IE (Ireland)	3.98E-01	1.05E-03	6.72E-05	5.55E-05
IN (India)	1.88E+00	1.01E-02	1.29E-03	5.60E-04

JP (Japan)	7.84E-01	1.16E-03	1.87E-04	9.01E-05
IT (Italy)	4.23E-01	1.07E-03	1.42E-04	7.58E-05
MT (Malta)	6.83E-03	2.98E-05	2.13E-06	2.45E-06
LT (Lithuania)	1.33E-01	1.01E-03	1.85E-04	5.49E-05
LV (Latvia)	1.55E-01	1.15E-03	2.37E-04	6.89E-05
NL (Netherlands)	4.01E-01	8.20E-04	1.68E-04	1.02E-04
NO (Norway)	2.25E-02	1.89E-05	3.60E-06	1.47E-06
NZ (New Zealand)	1.73E-01	2.30E-03	8.54E-05	4.10E-05
PL (Poland)	1.68E+00	4.13E-03	5.75E-04	2.82E-04
PT (Portugal)	1.47E-01	9.16E-04	1.58E-04	1.02E-04
RO (Romania)	4.36E-01	2.88E-03	2.68E-04	1.57E-04
SE (Sweden)	4.07E-02	3.70E-04	7.53E-05	2.62E-05
SI (Slovenia)	2.82E-02	4.56E-04	7.31E-05	4.29E-05
US	5.32E-01	6.62E-04	8.61E-05	4.86E-05

4.3.3 Case 3: the world fleets (see Fig. 17) applied to each flagged nation (27 countries).

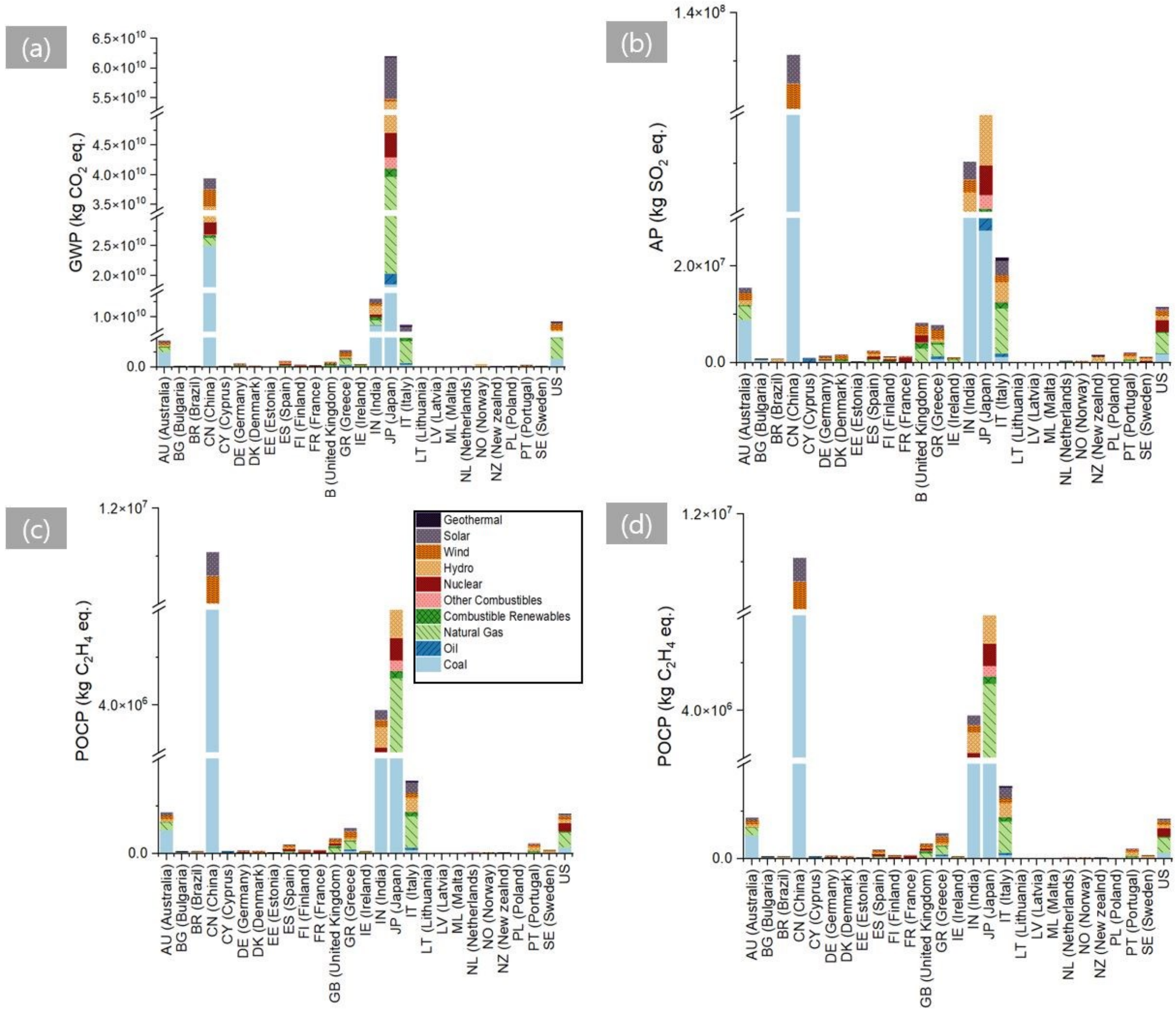


Fig. 20. Comparison in environmental impacts of world fleets according to their flag registration.

Now we are more interested in which countries might produce higher emissions than the others when adopting the battery-powered ships. In Case 3 the total vessels were grouped by their flag state (the country of ship registration). Then, they were assumed to be operated at the coastal areas of their flag states. For example, according to Fig. 17 (d), about 165 ships have been registered as flag state of China so that those vessels are assumed to be operated off the coast of China while charging the battery with China's inland electric grid. Since Japan and China have a large number of ships under their registration, the environmental impacts were also revealed high.

Fig. 20 shows the results of the environmental impacts for ships corresponding to the actual flag. Unlike Cases 1 and 2, where China, Japan, India, and Italy were found with the greatest emissions, results were highly influenced by the number of ships in their flag registration. Given that 942 ships with Japan flag and 165 ships with China, Japan shipping contributes to more GHG emissions than China. However, the other environmental impacts of AP, EP and POCP show that China shipping yields more emissions than Japan. These results are driven by China's high dependence on coal (60%), compared to Japan with coal (30%) and natural gas (30%) for electricity production. Similar trends can be found in another example. Remarkably, Greece has more ships than China, but environmental impacts are relatively lower than Chain. It can be seen Greece harnesses the high level of wind and solar energies for the national power grid, but China overly relays on coal higher than 60%, which makes a great distinction in cleaner shipping between those two countries.

The comparison between the US and China is also noteworthy. The US has 122 ships, so there is no significant difference from the number of ships in China. However, China has three times higher GWP than the United States and approximately ten times higher in AP, EP and POCP for the same reason.

This finding implies an important message to the future shipping on how to manage the low emissions in a great number of world fleets. Again, it can be confirmed that the method of generating electricity has a significant influence on holistic environmental impacts from shipping activities.

In summary, the question remains that the impact of battery use on the environment is far from the zero emissions the global maritime industry is ultimately trying to achieve.

5 Discussion

5.1 Contribution to demystifying zero emissions with battery-powered ships

With growing pressure on global environmental issues, the marine industry has been grappling with adopting various alternative energy sources as marine fuels. On the surface, those energies are thought to bring the shipping activities to a more 'green' and 'sustainable' realm. However, this research has demonstrated that those energies may dangerously misguide us to adverse outcomes when deconstructed without a proper understanding of their environmental benefits and harms. Research findings reveal that there are large variations by country in terms of the upstream emissions. This implies that even if a battery-powered vessel is environmentally profitable, there may still be a large distinction in reducing emission levels that highly depend on power production method and the source of energy. Germany, for example, uses less than 30% of fossil fuels in its national electricity grid, but the United States has about 50% and China has more than 60% reliance on conventional fossil fuels. It confirms that two identical electric-battery-powered vessels can bear completely different environmental performances according to the location of operation. As a result of a study of 36 countries, European countries (conducting eco-friendly power generation) clearly showed better environmental impact than diesel fuel propulsion, but Asian countries generally turned out to be less effective in the environment compared to diesel fuel propulsion. As green energies, it is easy to find cases that are often more harmful to the environment than conventional fossil fuels. This is a matter that we must realize. In the end, this paper comes into a bit skeptical conclusion to the fundamental question of whether electric propulsion vessels are truly green vessels; it guides us that is not only a matter of battery-powered ships but a matter of national electricity grids. In fact, the findings suggest how far we are to ultimately make battery-powered ships a cleaner option.

5.2 Contribution to suggesting the future environmental methods and practices

According to IMO 4th GHG study, GHG emissions from the global shipping (about 60,000 ships) were estimated to be 1,076 million tons in 2018 (Joung et al., 2020). Based on this number, the cumulative GHG emissions over the next 45 years[5] can be estimated at 48.4 billion tons or 4.84×10^{13}

[5] Considering ship lifespan of 45 years, all global ships were assumed new built for the sake of a simple calculation.

kg CO_2 Eq. This figure does not make far difference than GWPs driven from Case 2 analysis with merely about 5,500 ships (see Fig. 19) in this research. It is simply because the IMO report purely estimates emissions from shipping activities (or often called ‘down-stream’ or ‘tank-to-wake), whereas this research adopts a holistic approach which includes ‘up-steam’ or ‘wake-to-tank’ phases as well. In other words, if taking the conventional practices on environmental assessment, the analysis results throughout this research will indicate ‘zero’ for all battery-powered ships regardless of countries simply because that plug-in battery ships do not produce emissions during operation (no emission in down-stream phase). In other words, such conventional practices both deliberately and inadvertently underestimate the real harms of using battery powered ships by excluding the upstream emissions.

Over the lifetime, a ship is engaged in various activities leading to costing money, consuming energy, and producing emissions. To estimate the overall environmental impact of the vessel in question, the flows of energy and emissions pertinent to every single ship activity in various life stages need to be tracked and analyzed. Given this, the adequacy of these IMO environmental measures - known as EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Indicator) - remains in doubt as they are too vague to provide practical assistance in evaluating the overall environmental performance of marine vessels.

5.3 Guidelines for future study directions

The research findings offer tremendous insight into the direction of future policies and regulatory frameworks across the world shipping. On the other hand, this research also provides a significant message to other industries. For instance, the number of global electric vehicles have greatly increased over the past decade, driven by national policies and technology advancements (see Fig. 21).

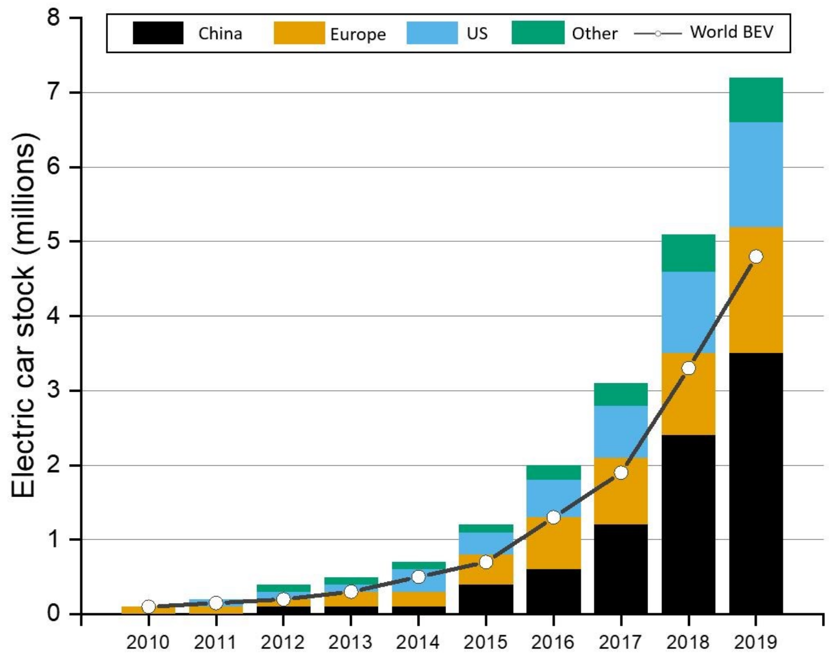


Fig. 21 Trend of global electric vehicles from 2010 to 2019 (IEA, 2020) ; BEV = battery electric vehicle.

Electric vehicles, which grew by 60% annually from 2014 to 19, totaled 7.2 million units; 47% of which were operated in China. Indeed, electric vehicles 100 % rely on the national electricity grid. As discussed earlier (see Fig. 6), China's electricity relies on more than 60% coal-based electricity production. It casts another doubt on whether the global trend of the surge in the number of electric vehicles is adequate; especially for using electric vehicles in China and US. Although more in-depth investigation is needed as future work, based on the ground of this research, the answer would be 'no'.

For the environmental protection from a short sea shipping, there were some interesting researches that promote hybrid operational routes between motorways and short-sea shipping to minimize air pollutions. Vallejo-Pinto et al. (2019) proposed iso-emission map which enables to identify the optimal routes and transport means in consideration of geographical conditions. The excellence was demonstrated with a case study of the sea Gijon-St. Nazaire. Kotowska (2016) introduced a method for cost and emission estimation in combination between land-short sea transport chains in comparison to conventional road transports. As suggested, hybrid transport (a combination of short-distance sea transport and highway) deserves further investigation into whether a better solution for environmental protection can be found from an LCA point of view.

6 Conclusions

Research findings and key messages from this paper can be highlighted as below:

1) The impact of zero emission from battery-powered ships has been misunderstood because the key factors determining the ship's overall environmental impacts are highly associated with the energy sources used to generate electricity. Some interesting results were found in the comparison in the environmental impacts pertinent to the electric grids among the India and some other countries with high reliance on fossil-fuels. Assuming that the same ship was dispatched to the coastal area of India, and on the same principle, charging electricity from the national grid overnight, adverse results were turned out.

2) This paper made it clear that the battery-powered ships operating in countries with high reliance on fossil-based energy resources contribute to much greater environmental impacts than the same ships dispatched to countries with a high level of renewable energy sources. Those findings strongly argue that cleaner shipping is not only a matter of battery ship development but also the transition of the national electricity grid.

3) This comparative analysis recurs the fundamental question of this research; whether battery-powered ships will be ultimately the best solution for maritime environmental protection. The answer should be "no" as it is highly sensitive to the locations where the hybrid ships are in service. In fact, these findings go off the alarm to the public who may have false confidence with the environmental benefits of electric cars and ships.

4) The conventional approaches/ practices of assessing the environmental impact assessment were identified as a causation of categorizing the battery powered ships into 'zero emission ship' which widely misguide global and local policies to achieve greener shipping. It is because those tools were focused on the ship operation phase (down-stream) alone while disregarding energy production and supply phases (up-stream) in environmental assessment. On the other

hand, the danger of over-reliance on those limited tools was clearly identified through this research. The LCA results vividly showed the greatness of the environmental harms of battery application to ships if not used properly. In some countries with high coal-based electricity production, the battery application was revealed even worse than the conventional diesel ships in a holistic point of view. This research set off an alarm for those existing approaches that misleads the as possibly being more harmful than helpful for cleaner shipping. A key message of this research is to point out the urgent need to adopt LCA as a standard for assessing the environmental performance of marine vessels.

5) The association in the environmental performance of the battery-powered ships with the electricity production method is so strong that this paper suggests further steps for investigating other types of marine fuel sources as well as energies attracting from other industries. Hydrogen and ammonia along with plug-in batteries, as future marine energy sources, are drawing more and more attention for the same reason such as not emitting GHGs during ship operations. The problem is that those energies due largely come from fossil-based energy sources such as natural gas. In addition to this, while the number of global electric vehicles is increasing significantly, this paper raises another question as to whether those energy sources and vehicles can ultimately contribute to the global environment. It is highly believed that the method applied in this paper, thereby key findings, can be useful and pioneering guidance in answering those questions.

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