Is LNG the solution for decarbonised shipping?

Nitin Agarwala

Research Fellow, National Maritime Foundation, Delhi, India

ABSTRACT
The Paris Agreement has exerted tremendous pressure on the maritime industry to reduce carbon emissions. Since then, the industry has experimented with numerous technological, operational and incentive methods. Even though to date no concrete method or technology has proven to be a potent decarbonisation candidate, using LNG as a bunker fuel has shown some positive prospects in the reduction of atmospheric pollution. While the induction of LNG has been driven by a combination of environmental benefits and attractive fuel prices, especially for new construction, its actual use has received mixed acceptance. These mixed reactions have created a general sense of uncertainty about the benefits LNG can provide towards decarbonisation that has resulted in unease within the maritime shipping industry. Using desk-based qualitative research, the author analyses LNG as a possible fuel to achieve decarbonisation by the maritime shipping industry. In doing so, the evolving controversies associated with acceptance of LNG as a decarbonising fuel to meet the targets of the Paris Agreement have been analysed. Eventually, the future of LNG as an alternate fuel for the maritime shipping industry is evaluated and the role LNG can play as a future bunker fuel for decarbonisation of the maritime shipping industry is discussed.

Introduction
The requirement to reduce carbon emissions as part of the Paris Agreement forced the International Maritime Organisation (IMO) to experiment with numerous technological, operational and incentive methods that included fuel-based, technology-based, operation-based, and incentive-based initiatives (IMO, 2018, 2018a). However, no clear winner of a solution has emerged that can be utilised beneficially by the maritime shipping industry. With time running out, changing from Heavy Fuel Oil (HFO) to Liquefied Natural Gas (LNG) is emerging as possibly the best available solution. While the use of LNG encourages reduction of SOx, NOx, CO2 and particulate matter emissions, studies indicate that the use of LNG cannot be considered as a long-term solution to meet the commitments of the Paris Agreement and move to a net-zero emissions regime by 2050 as committed by the IMO.

Even though lower carbon content in LNG permits a theoretical reduction in emissions, it is unclear if usage of LNG can provide Greenhouse gas (GHG) benefits over the entire lifecycle of LNG when compared to conventional fossil-fuel bunkers. This is primarily because LNG is a form of liquefied methane, and methane as a gas is a highly potent GHG (nearly 86 times and 36 times more potent than CO2 over 80 and 100 year cycle respectively) (IPCC, 2013) with a much greater warming potential than CO2. When used as a fuel, the unburned methane that is emitted in the atmosphere (called methane slip) can entirely offset the theoretical GHG benefit of LNG. Furthermore, the advantages of LNG consider the Tank-to-Wake life cycle rather than the Well-to-Wake cycle, thereby providing a false sense of confidence towards the possible advantages LNG has to offer as a decarbonising fuel.

This limitation notwithstanding, shipowners have begun to focus on the use of LNG as an alternate fuel due to economic considerations and the mandates of decarbonising as promulgated by IMO (IMO, 2018). It is no wonder that by 2020, nearly 22% of the order-book for new ships was for alternative fuel ships of which nearly three-fourth were to be LNG-fuelled. This said, the growing uncertainty regarding the possible GHG benefits from LNG has created discomfort amongst the maritime shipping industry. It hence becomes important that we understand if LNG has the requisite potential of being a decarbonising fuel for the maritime shipping industry and the range over which its use can be beneficial.

Accordingly, there is a need to discuss the evolving discomfort of the stakeholders in accepting LNG as a decarbonising fuel to meet the targets of the Paris Agreement, the future of LNG as an alternate fuel for the maritime shipping industry and the role LNG can play as a future bunker fuel for decarbonisation of the maritime shipping industry which is the prime motivation of this article.

The article is organised to begin with the driving forces that have helped LNG to being a possible decarboniser for the maritime shipping industry.
merits and demerits of the use of LNG are discussed next along with the related controversies that have created the undesired discomfort in the industry before understanding the range over which the use of LNG would be beneficial to achieve decarbonising. In addition, the possible implications on both policymakers and the industry are discussed to complete the discussion and understanding. In doing so, efforts to answer if LNG is the possible solution to decarbonise the maritime shipping industry will be addressed.

Background

Studies on global warming indicate that both natural and anthropogenic factors are contributors to climate change. However, the contribution of the natural factors (such as changing intensity of the Sun, natural systems such as forest fires, oceans, wetlands, permafrost, mud volcanoes, earthquakes, volcanic eruptions, and changes in naturally occurring greenhouse gas concentrations of \( \text{CO}_2, \text{CH}_4, \) and \( \text{N}_2\text{O} \)) is way too small to be of any serious consequence when compared with the influence of anthropogenic events (Agarwala & Polinov, 2021). Accordingly, the anthropogenic GHG emissions need to be reduced drastically by all the polluting sectors, one of which is the transportation sector that includes maritime shipping.

Even though maritime shipping is much more efficient than its land and air counterparts and contributes a mere 2.2 % of the global GHG, in order to meet the commitments of the Paris Agreement, the IMO agreed in October 2016 to develop a comprehensive strategy to address GHG emissions from maritime shipping through long-term goals. This in return has put the maritime shipping industry under tremendous pressure to reduce carbon emissions and has led to numerous technological, operational and incentive based options and studies. Even though numerous options have been experimented with in this regard, to date, there is no concrete method or technology that can help the maritime shipping achieve the desired decarbonisation.

Since the primary backbone fuel used by shipping has been the fossil fuel that forms a major portion of the life-cycle cost of a ship even today, the focus of IMO has been to reduce GHG emissions to 50 % by 2050 with a 40 % reduction of \( \text{CO}_2 \) emissions by 2030 and 70 % by 2050 (IMO, n.d.) through change of fuel used. It is important to mention that as the type of fuel changes, so does the emission of \( \text{CO}_2 \), \text{SOx}, \text{NOx}, particulate matter and methane change with inefficient ships emitting the maximum pollutants akin to inefficient vehicles on the road. Accordingly, to address \text{SOx} emissions from HFO that has high sulphur content, the International Convention for the Prevention of Pollution from Ships (MARPOL) had set a reduction of sulphur content in bunker fuel from 4.5 % in 2000 to 0.5 % by 2020. They have also established the Emission Control Areas (ECA) where the emission regulations have been made stringent in an effort to address \text{NOx} emissions from marine gas oil (MGO) and marine diesel oil (MDO).

Furthermore, in an effort to further incentivise reduction of emissions from shipping, the IMO through the Marine Environment Protection Committee (MEPC) formulated term goals spread over short, medium, and long periods (IMO, 2018). The short-term measures (2018–2023) are three-pronged. These efforts include adoption of the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for operational ships (MEPC 62) as a first step. The next step looks at promoting both technical co-operation and transfer of technology to ensure that energy efficiency of ships is encouraged (MEPC 65). The third level includes collection of data on fuel oil consumption to improve the existing strategy (MEPC 70). Based on these short-term measures, the medium (2023–2030) and long-term (beyond 2030) measures aim to implement market-based mechanisms (Agarwala et al., 2021) with digitalisation looking to play an ever increasing and important role in achieving decarbonisation (Agarwala et al., 2021; Agarwala & Guduru, 2021). To ensure that these efforts are successful and encourage clarity and greater participation by stakeholders, IMO has identified a number of areas to be addressed. One of these efforts is to “peruse the development and provision of zero-carbon or fossil-free fuels” which is still to be identified and developed. Till a zero-carbon or fossil-free fuel is identified; the next best fossil-fuel that can provide reduced emissions as compared to the largely used MDO, HFO or Very Low Sulphur Fuel Oil (VLSFO) is the Liquefied Natural Gas (LNG) which needs to be utilised to achieve decarbonisation of the maritime shipping.

As a fuel oil, LNG owes its popularity to very little sulphur hence low \text{SOx}, low \text{NOx}, low particulate matter and \text{CO}_2 emissions, supported by low costs when compared to MGO, HFO or VLSFO thus making economic sense to invest in an LNG fuelled ship. It is no wonder that since 2010 the LNG fuelled vessels have increased consistently between 20 and 40 % (SEA-LNG, n.d.). Today, there are 175 LNG ships in operation, 145 LNG-ready ships (ships burning conventional fuels but having design features suitable to permit conversion at a future date based on existing Class requirements) and 195 on order (Statistica, 2021). Most of these vessels operate in Europe due to the strict sulphur content regulations in the ECA of the North Sea and the Baltic Sea. As these ECAs expand in their size, the size of the LNG fuelled vessels is increasing. Similarly, the LNG bunkering infrastructure for refuelling these ships is also increasing with major facilities at the Port of Rotterdam.
Such are worth CO gap matures. The compared (a).
The Port of Amsterdam (Netherlands), the Port of Zeebrugge (Belgium) and the Port of Barcelona (Spain). However, these bunkering facilities are limited to Europe and some parts of North America and East Asia.

**Merits of using LNG**

The use of LNG displays a number of benefits when compared to other fossil fuels. Studies confirm that the GHG emission per megawatt hour of electricity generated by LNG is the minimum at 493 ± 9. This is much lower than that produced by coal and oil at 865 ± 18 and 728 ± 18 respectively (CSIRO, 1996). Such studies confirm the merit of using LNG to reduce the environmental GHG emissions. It is worth mentioning that the currently recorded emissions from LNG are likely to reduce as technology matures. This would help increase the advantage gap of LNG as the technology used for coal and oil is already mature and little improvement in GHG emission is expected for these fuels (Arteconi et al., 2010).

On the emission side, LNG generates 45–55 % of CO₂ when compared to coal (James et al., 2019). LNG emits nearly no Sulphur Oxide (SOx) or Particulate Matter (PM). It emits less NOx (nitrogen oxides) and CO₂ than other fossil fuels on combustion primarily because sulphur is removed during the pre-liquefaction process. As a fuel, LNG is safer as its specific gravity is lighter than that of air. This allows it to easily diffuse in air making it less risky during an explosion. With proven reserves surpassing those of oil, LNG has the ability to provide a stable supply for over 50 years making it a suitable candidate as a fuel for the maritime shipping industry.

When we look at the use of LNG till 2050, numerous benefits are possible due to the improvement in technology from 2020 to 2050 through 2030 (SEA-LNG, 2021). These improvements are likely to reduce GHG emissions and hence provide a positive view-point for use of LNG as a fuel for maritime shipping. Some of these advantages are likely to occur:

(a) Reduction of methane emissions in the LNG supply chain of 15 % by 2025 and of 35 % by 2030 based on actual initiatives and communicated targets.

(b) Reduction of overall GHG emissions of 4 % by 2025 compared with 2020 and of 9 % by 2030.

(c) Reduction of absolute GHG emission values to 16.1 g CO₂-eq/MJ (LHV) by 2030 from 17.7 g CO₂-eq/MJ (LHV) in 2020 while that for standard fuel oils would range from 14.0 for VLSFO, to 14.9 g CO₂-eq/MJ (LHV) for MGO.

(d) An increase in advantage in GHG emissions over the full lifecycle of

(ii) 24 % from 23 % in 2030 and 24 % from 14 % for Otto-cycle engines in 2-stroke slow speed diesel-cycle engines

(iii) 22 % from 6 % for Otto-DF and 21 % from 14 % for Otto-SI in 2030 in 4-stroke medium speed engines

(e) In regard to the combustion process of the fuel in the engine, the likely benefits expected by 2030 are 27 to 30 % for 2-stroke slow speed engines (theoretical max. benefit – 31-33 %) and 28 % for 4-stroke medium speed engines (theoretical max. 30 %).

**Demerits of using LNG**

While numerous benefits towards GHG emission exist by using LNG as a fuel for ships, there are demerits that need to be addressed and minimised to ensure that the required benefits can be maximised. Usually, the analysis for GHG emission from LNG is done only at the Tank-to-Wake level which provides the GHG emissions as produced during the engine combustion. One may consider these calculated advantages as skewed as to get a complete and correct picture it is essential to consider these emissions over the entire lifecycle of LNG. If not done so, the unaccounted GHG emissions would be transferred to another industry which effectively disallows meeting the overall GHG reduction of the planet. This entire lifecycle for LNG (Well-to-Wake) consists of both the supply system (Well-to-Tank) and the combustion process (Tank-to-Wake) and needs to be considered. Accordingly,

(a) For Well-to-Tank (LNG supply system) the GHG emissions need to considered for

(i) Gas production, processing and pipeline transport to liquefaction plant.

(ii) Gas liquefaction and purification.

(iii) LNG carrier transport based on distance travelled and use of carrier.

(iv) LNG terminal operations and bunkering.

(b) For Tank-to-Wake (combustion process) the expected GHG emission reduction for LNG-fuelled engines compared with VLSFO fuelled engines will vary based on the type of the engine. Accordingly, this is expected to be 20 to 30 % for 2-stroke slow speed engines and 11 to 21 % for 4-stroke medium speed engines.

(c) Overall, for the Well-to-Wake (full cycle) the benefits are highly dependent on the engine technology installed. The expected GHG emission reduction for gas fuelled engines when compared with VLSFO fuelled engines are between 14 to 23 % for 2-stroke slow speed engines and 6 to 14 % for 4-stroke medium speed engines.

Such a break indicates that when calculated for the entire lifecycle (production, delivery, processing,
shipment, receipt, storage and end-use (Abrahams et al., 2015; API, 2020; Roman-White et al., 2019), LNG cannot be considered as a decarbonising fuel and a possible solution for a net-zero emission future. While LNG has a low environmental impact, some other general disadvantages that dissuade its usage as a fuel for maritime shipping are:

(a) The need to install new engines that can use LNG fuel.
(b) The need for capital investment for equipment to store and liquify LNG prior use.
(c) Likely increase in construction cost by 15 – 30 % than conventional ships due to advanced and controlled construction technology.

The controversy

While the environmental benefits of LNG as a possible alternate to marine fossil fuel are clear in regard to local pollutants such as Sulphur oxide (SOx), Nitrogen oxide (NOx), and particulate matter (PM), various studies have demonstrated different GHG impacts due to the use of LNG. These different outcomes are reported due to different assumptions (methane emission from LNG and methane slip in ship engines), methodologies and data used for these studies. In addition, since some of the LNG engines undertake Selective catalyst reduction (SCR) or Exhaust gas recirculation (EGR) to reduce the generation of NOx, it is difficult to judge the actual impact of NOx when using LNG fuel. This has resulted in numerous controversies to disallow unanimous acceptance of LNG as a decarbonising fuel for maritime shipping. Some of these controversies are listed and discussed here to provide the sense of confusion and discomfort the shipowners face in shifting to LNG as a decarbonising fuel.

Controversy 1 – Lifecycle consideration of LNG

For a complete understanding of the GHG impact caused by LNG, it is essential to consider the entire lifecycle from Well-to-Wake that includes Well-to-Tank (LNG supply) and Tank-to-Wake (combustion processes). Such a consideration is essential to avoid a shift of burdens from one stakeholder to another within the supply chain and to establish a level playing field for all fuel comparisons with an ambition to develop a low- and zero-carbon maritime shipping. However, this analysis is made difficult due to the presence and use of different engine technologies (2/4 stroke engines, single/dual fuel combustion cycles, efficiencies, exhaust gas cleaning systems etc.) and different fuels (MGO, MDO, VLSFO, HFO) by the maritime shipping industry with their geographically specific supply chains. It thus becomes important to differentiate the possible variables of engine technologies and fuel used by different ship type, size and operational parameters when drawing conclusions with regard to LNG as a decarbonising fuel. However, when these studies recommending LNG as a decarbonising fuel are evaluated, one wonders if these studies are reliable or not and if they have considered the full lifecycle of LNG fuel or not.

Controversy 2 – Interest of stakeholders to invest in an uncertain scenario

Since there is no known clear winner technology that can achieve net-zero emission for the maritime shipping industry and the fact that LNG provides an advantage of “zero sulphur content,” 25 % reduced CO2 emissions, low-nitrogen emissions and competitive pricing when compared to VLSFO to address a growing environmental concern, the use of LNG-fuelled vessels is expected to grow. However, since its usage is not net-zero emission compliant, LNG can be best considered as a “transition” fuel rather than a long-term solution towards zero-carbon emissions for maritime shipping. This thus creates a divide in the acceptance of LNG as a “transition fuel” and the potential advantages it has to offer as a potential decarbonising fuel. Hence it follows that if LNG is used as a transition fuel, the path to net-zero emission will need to follow multiple energy transitions. This would require the maritime shipping industry to first move from oil to LNG bunkers and then from LNG to net-zero fuels. This would make the process of moving to net-zero technology difficult, cumbersome, complicated and prolonged. Hence one wonders if the stakeholders would be keen to invest in these multiple transitions especially when the industry prefers to minimise costs and shipowners want to spend only on mandatory issues with minimum down time.

Controversy 3 – Need to spend for developing bunkering

In order to encourage the use of LNG, both LNG bunkering and manufacturing will need to be encouraged/ increased. This would require massive investments for new infrastructure such as pipelines, liquefaction facilities, export terminals, and tankers to support the LNG bunkering and manufacturing industry (NRDC, 2020). Currently, such facilities are limited to developed countries and investments will be a major challenge to introduce especially in other parts of the world where the focus is towards sustenance and not climate change. This makes one wonder if the lack of these investments would make the transition to LNG difficult.
Controversy 4 – What are the actual emission gains of LNG?

The Well-to-Tank GHG emissions of LNG (from extraction, transport, liquefaction, and re-gasification) have been found to be almost equal to the emissions produced from the actual burning of the gas (Tank-to-Wake). This effectively doubles the impact of LNG on climate change. Studies have shown that these emissions can be broken down to gas production, processing and pipeline transport to the liquefaction plant that account for 32.5%, emissions due to energy consumption and methane emissions, gas liquefaction and purification accounting for 49.5% emissions due to energy consumption, LNG transportation that produces 14% of emissions based on distance travelled and the utilisation of the LNG carrier and the LNG terminal operations and bunkering that accounts for 4% emissions due to energy consumption and methane emissions. One wonders about the overall gains from LNG when considering the full lifecycle. Will such a shift in analysis encourage the use of LNG as a decarbonising fuel to achieve net-zero emission targets as set out by the Paris Agreement?

Controversy 5 – Can green energy support use of LNG?

LNG falls short of lifecycle GHG emissions when compared to renewables. Emissions from solar power are less than 7% of LNG emissions while those from wind power are less than 2% of LNG emissions (Gowrishankar & Levin, 2017). This effectively means that if renewables were to be used for LNG production the overall lifecycle emissions created by LNG would reduce making it lucrative and effective for use. Hence, one wonders when green energy would become the norm to reduce the overall lifecycle GHG emissions.

Controversy 6 – Is the data used for studies accurate?

The greatest disadvantage of LNG is the production of methane which is the main component of LNG. Methane by nature does not remain in the atmosphere as long as what carbon dioxide does, but the impact it has on climate change is more than 80 times stronger in the short-term (20-year) time frame and 28 times stronger over the long-term (100-year) time frame and hence use of LNG which produces high quantities of methane is considered detrimental for climate change. Though methane slip can be addressed by using high-pressure engines it is a concern for low-pressure engines. These outcomes are based on different assumptions (methane emission from LNG and methane slip in ship engines), methodologies and data used during these studies. One wonders if the existing studies are reliable and comparable since each one of them tends to use different base data. Do these studies give confidence for use of LNG as a decarbonising fuel?

Discussion

In the preceding sections the advantages offered by LNG as a decarbonising fuel have been discussed. While there are numerous benefits as seen, LNG as a fuel does not provide the required net-zero emission targets as recommended by the Paris Agreement when the full lifecycle emissions are examined. Hence, in most discussions the LNG fuel is considered as a “transition” fuel till a net-zero emission fuel can be developed. However, like any other field, the use of LNG fuel as a decarbonising fuel has two camps of which the nay-sayers have created a controversy to debate the use of LNG as a decarbonising fuel.

When addressing the controversies, one notices that while there is merit towards the concerns raised, it is important to accept that today humanity stands at a cross-road wherein his limited technical knowledge does not provide a clear winner net-zero emission fuel. This said, the best option of the numerous ones tried and available happens to be LNG which has positive advantages which would only increase as the technology is refined. Furthermore, some negative concerns such as “methane slip” have been adequately addressed over the years by improving engine technology. Wärtsilä, for example, has been able to cut the methane slip from its dual-fuel engines from 16 g/kWh to 2–3 g/kWh (nearly 85% reduction) since 1993 by using high-pressure engines (Wärtsilä, 2020).

Similarly, since no clear net-zero emission technology is known to date, there is no reason why humanity should not commence its efforts of decarbonisation today rather than to wait for an unknown, uncertain, and unproven technology of tomorrow which may never be available or be available by when it is too late. While this is done, the advantages calculated and considered should be on a Well-to-Wake (full lifecycle) basis and not just on the Tank-to-Wake basis (combustion technology) alone.

Though the down-side of this approach is that by accepting LNG fuel, the investments made towards LNG modernisation and infrastructure may drive investors to derail future developments of net-zero emission fuels. However, since the maritime industry is inherently slow towards change (Agarwala, 2021) as long as the drive for future developments is monitored and driven by the IMO, there is high possibility that if and when the advanced fuels are developed, the change would happen like many other environmental initiatives driven by the IMO. It is also possible that advances in technologies related to the Well-to-Wake may eventually improve the advantages of LNG usage.
thereby providing a winning solution to the maritime shipping industry. This is a calculated risk which humanity will have to take as some action is better than inaction to address the growing challenges created by climate change.

One needs to also accept that most studies undertaken for new technologies are driven out of commercial interest and at times skewed in favour of the funding agency. This notwithstanding, the numerous studies undertaken so far for LNG as a decarbonising fuel has shown that there is a definite reduction in GHG emissions by using LNG gas. While the absolute figures may vary, the advantages exist and it is important that these advantages are cashed for the benefit of the future generations.

As on date most of the efforts in the lifecycle of LNG are driven by other carbon emitting fuels. If in case these carbon emitting fuels are substituted with renewable energy the net benefits accrued towards decarbonisation would increase. This would also reduce full lifecycle GHG emissions for LNG which would eventually strengthen the case for use of LNG as a decarbonising fuel for the maritime shipping industry.

It is important to mention that for regions where stricter emission norms are in force, LNG as a ships fuel is the only available option. As these controlled ocean spaces are increasing in size, the number and size of LNG ships are increasing with LNG being positioned as an effective and economically beneficial alternative fuel that can contribute to the proposed GHG emissions reduction from ships. Studies show that if the global marine transport fleet of today (fuel consumption per engine based on 2015 data) were to completely switch to LNG as a marine fuel, there would be a GHG emission reduction of 15% due to this switch alone.

With advances in engine technology to address methane slip and use of liquefied biomethane and synthetic methane these reductions can be further improved (SEA-LNG, 2021). In this regard, Intelligent control for Exhaust Recycling (ICER) that aims to recirculate methane in the exhaust to reduce the residual methane before ultimately escaping into the atmosphere (WINGD, 2021), oxidation of methane by catalysts by using methane oxidation catalyst system (MOL, 2022), and implementation of high-pressure gas injection for reduction of methane emission by 70–90% (Imhof et al., 2013) are some technological advances addressing the issue of methane slip.

Today, high-pressure dual-fuel diesel engines are considered to be proven 2-stroke engines with virtually no methane slip, and low-pressure 2-stroke slow speed Otto cycle engines offer nearly 50% reduction in methane-slip (Ushakov et al., 2019), there is a need to develop 4-stroke LNG engines of similar capabilities (Lindstad & Rialand, 2020). While such advancing technologies may help address the reduction of methane slip, the need of the hour is to install methane monitoring devices in ship exhaust system to understand methane emission better and provide a baseline for researchers to improve their solutions (Balcombe et al., 2022).

**Alternatives available**

As discussed, the currently known technology and processes do not assist in achieving the GHG emissions target of 50% set by IMO for 2050 through change of fuel alone. It is hence necessary that other measures such as improvements in design and technology along

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*Figure 1. Candidate areas for decarbonisation – as recommended by IMO (Source: Agarwala et al., 2021).*
with changes in operational procedures such as slow steaming are explored. A mix of these would eventually help to achieve the desired net-zero targets of emission. Accordingly, numerous measures have been recommended by the IMO as seen in Figure 1.

Accordingly a number of fuel-based, technology-based, operation-based, and incentive-based techniques have been experimented with. On the fuel side, renewable fuels have been experimented with as seen in Table 1. A detailed review of the alternative fuels available for maritime transportation (Al-Enazi et al., 2021) shows that both hydrogen and ammonia have the required potential to completely replace fossil fuels with LNG as the readily available transition fuel for the maritime shipping industry. Despite the concerns over methane slip when using LNG, the gas still currently outperforms methanol and ammonia and hence is considered as the best possible alternative for decarbonisation. However, since the full lifecycle emissions of the gas do not match the zero-emission targets of the IMO, the use of LNG is limited to being a "transition" fuel in place of being a decarbonising fuel for maritime shipping. Yet another interesting fuel is nuclear which can provide the required decarbonisation, however, the constraints of technology and human resources compounded by security issues do not provide the required environment for use of nuclear as a fuel for commercial shipping.

In order to achieve the required targets of the Paris Agreement with the known technology of today, emissions need to be reduced by nearly 80% for which battery or hydrogen fuel cells are the possible options (Bieker, 2021). However their use for the maritime shipping industry is still at the nascent stages. In recent years methanol has been developed as a potential alternate to fossil fuels in shipping by being biodegradable, safe to handle, and offering a pathway to carbon neutrality through the use of blue and green methanol in line with IMO’s decarbonising goals (Gateway Media, 2022).

While we have discussed some alternatives available, the road to net-zero emission is long and winding and not limited to the use of alternate fuels alone. In effect to meet the Paris Agreement target a number of multi-pronged efforts are essential that requires a multi stakeholder approach and involvement some of which include the following.

(a) Stakeholders associated with maritime shipping need to work towards common decarbonising goals and be aware of the environmental and economic impacts and benefits associated with recommended transition and should be supportive to the efforts being encouraged. This said it is essential that a certain amount of questioning to ensure the correct direction is maintained but such a querying should be constructive rather than being counterproductive.

### Table 1. Renewable fuels towards decarbonisation (Source: IRENA, 2021).

| Renewable fuels | Characteristics |
|-----------------|-----------------|
| Advanced biofuels | - A viable short-term option for the maritime shipping industry as current rules allow fuel blends of up to 20% without engine modifications. Tested to a maximum blend of 30%.  
- 100% methanol engines are a proven technology.  
- Cost range of production is USD 72–238/ MWh.  
- Sustainability of biomass feedstock used is a critical factor.  
- Current focus is on use of waste fats, oils and greases (FOGs) to produce fatty acid methyl ester (FAME) biodiesel, hydrotreated vegetable oil (HVOs) that do not impact food security, and land availability while use of other feedstock not yet mature.  
- Competition will exist for suitable feedstock for fuel production. |
| Biomethane | - Can play a limited role.  
- Production costs highly dependent on feedstock availability and market price. Would have a wide cost range of USD 25–176/ MWh.  
- Biogas produced via anaerobic digestion is an attractive option for displacing LNG.  
- Due to scalability and logistical issues, use of biogas may be more effective in end-use applications other than for shipping sector. |
| Hydrogen | - Green hydrogen (H₂) using fuel cells (FCs) and internal combustion engines (ICEs) recommended for short sailings/domestic navigation.  
- Indirect use of green H₂ for production of e-fuels considered critical for decarbonisation of international shipping.  
- Current green H₂ production costs range between USD 66–154/ MWh  
- As cost of electrolysers and renewable energies fall, cost of green H₂ will become competitive around 2030, and achieve cost of around USD 32–100/ MWh by 2050. |
| Renewable methanol, i.e., bio-methanol and renewable e-methanol | - Require little to no engine modification.  
- Provide significant CO₂ emission reductions.  
- Renewable e-methanol is of particular interest to the shipping sector.  
- The key constraint towards production of renewable e-methanol is availability and cost of a CO₂ supply not sourced from fossil fuels. |
| Renewable e-fuels, methanol and ammonia | - Considered the most promising fuels for decarbonising.  
- Ammonia more attractive due to its null carbon content.  
- By 2050, production cost of e-methanol expected to reach USD 107–114/ MWh due to reduced cost reduction of green H₂ and CO₂ capture technologies. |
| Renewable ammonia | - E-ammonia is likely to be the backbone for decarbonising international shipping in the medium and long term.  
- By 2050, production cost of e-ammonia is expected to be between USD 67–114/ MWh.  
- By 2023, validation of ammonia engine designs essential to unlock use of renewable ammonia.  
- Safe usage of ammonia possible as handled safely for over a century. |
(b) Airborne emissions in ports and inland waterways should be limited and controlled through strict regulations. Cold-ironing supported by renewable energy sources needs to be encouraged in ports to reduce emission of airborne pollutants and GHG during berthing and docking periods.

(c) Encourage carbon levy on fuels based on emissions produced to encourage quicker shift to renewable fuels and development of technology for net-zero emission fuels. In doing so encourage advanced liquid biofuels, biomethane and H2-based fuels.

(d) Boost efforts to develop engine technology capable of harnessing green H2-based fuels that can be deployed and scaled up.

**Conclusion**

Increasing GHG emissions in the atmosphere, with the major contribution being from anthropogenic efforts, has been identified as the major cause for climate change. In order to control these emissions certain targets were agreed upon during the Paris Agreement based on which IMO provided guiding targets for the maritime shipping industry in 2015. Since then numerous technological, operational and incentive methods have been tried out but to date no clear winner of a technology or a solution has emerged to achieve net-zero emissions. The next best solution available is found to be the use of LNG as a fuel which displays positive advantages towards emission reduction but falls short of achieving the IMO targets to 2050. Hence LNG as a fuel is considered only as a “transition” fuel and not a permanent solution to meet the targets of the Paris Agreement. This has resulted in down-the-middle split between the shipping operators and engine manufacturers thereby allowing a controversy to take shape that questions the very efficacy of LNG as a decarbonising fuel.

Accordingly the controversy and the way ahead have been discussed in the article. What emerges is that while there is merit in the controversy and the queries raised by the nay-sayers, the available alternatives are limited and a delay in shifting to LNG as a fuel for decarbonising, even if only for transition, may be detrimental for humanity since there is no certainty about the development of a net-zero emission fuel, its delivery timeline and if it would be successful.

Hence decarbonisation needs to start today through the use of LNG as the benefits it offers are definitely a positive step towards net-zero future. Eventually, some action is better than no action, especially for climate change the impact of which is being felt by humanity across the globe on a near regular basis and increasing on a daily basis. While there may be a requirement for the maritime shipping to undergo multiple transitions before reaching net-zero condition, LNG can be considered as a positive first transition towards decarbonising the maritime shipping. Once commenced, bioLNG and renewable synthetic LNG would only help greater emission reduction.

The overall road to decarbonising and achieving zero-emission will not be easy, especially for maritime shipping. While policies at the global and regional levels may help develop the desired zero-emission fuel the present known LNG fuel pathway is a clear, practical, and economically realistic route for decarbonising maritime shipping.

**Table of Acronyms**

| Acronym | Description                  |
|---------|------------------------------|
| CO2     | Carbon dioxide               |
| CH4     | Methane                      |
| ECA     | Emission Control Areas       |
| EEDI    | Energy Efficiency Design Index |
| EGR     | Energy Gas Recirculation     |
| FAME    | Fatty Acid Methyl Ester Biodiesel |
| FC      | Fuel Cells                   |
| FOG     | Fats, Oils and Greases       |
| GHG     | Greenhouse gas               |
| ICE     | Internal Combustion Engines  |
| IMO     | International Maritime Organisation |
| HFO     | Heavy Fuel Oil               |
| HVO     | Hydrotreated Vegetable Oil   |
| LHV     | Lower Heating Value          |
| LNG     | Liquefied Natural Gas        |
| MDO     | Marine Diesel Oil            |
| MGO     | Marine Gas Oil               |
| N2O     | Nitrogen oxide               |
| NOx     | Nitrogen Oxides              |
| OTTO-Df | Otto Cycle - Dual Fuel       |
| OTTO-SI | Otto Cycle - Spark Ignition  |
| PM      | Particulate Matter           |
| SCR     | Selective Catalyst Reduction |
| SEEMP   | Ship Energy Efficiency Management Plan |
| SOx     | Sulphur Oxides               |
| VLSFO   | Very Low Sulphur Fuel Oil    |

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**ORCID**

Nitin Agarwala [http://orcid.org/0000-0003-0916-3044](http://orcid.org/0000-0003-0916-3044)

**Disclaimer**

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