RECENT ADVANCEMENTS IN DIESEL TECHNOLOGY

Introduction

The production and consumption of fossil fuels has been instrumental in shaping the modern world, including lifestyles, economies, and the environment. Diesel fuel plays a central role in this fossil fuel-based world due to its high energy density and low volatility [1]. Multiple logistical and manufacturing industries use diesel to power their diverse and specialized fleet of machinery. As with any fossil fuel, the consumption of diesel fuel produces greenhouse gases including hydrocarbons (HC), particulate matter (PM), NOx, SOx, CO and CO_2 [2]. When these gases are released into the atmosphere, they contribute to climate change, increased rates of respiratory illness, atmospheric haze, and wildlife health issues [3], [4].

Regulatory bodies such as the United States EPA, the European Union, and the United Nations continually push for stricter greenhouse gas emissions regulations under their respective jurisdictions. Although beneficial to our society, health, and environment, these regulations often place a financial and logistical burden on industries where greenhouse gas emissions are inevitable. The trucking, shipping, mining, construction, agriculture, and forestry industries are examples of industries with high emissions due to their continued use of diesel fuel. To ensure compliance with these ever-changing regulations, companies must spend time and money purchasing and retrofitting their equipment, leading to increased overhead and downtime.

To better adapt to these regulations and ease their adoption among users, diesel fuel technology has experienced a renaissance within the last three decades. This paper examines several advancements in diesel fuel technology within the last two years, paying close attention to sustainability and efficiency, narrowing the focus to aftermarket fuel conditioners, renewable sources of diesel fuel, and legislative climate change reduction strategies. These advancements have been spurred by the standard push towards performance and cost-effectiveness, while simultaneously addressing sustainability concerns from the recent threat of climate change.

SulNOx Eco Trial

Diesel fuel conditioners, a type of fuel additive, are a class of chemicals used to reduce emissions and mechanical wear in diesel engines. These additives are infused with anti-gel chemicals to stabilize fuel consistency, cetane boosters for increased combustion efficiency, anti-oxidizers for shelf-stability, and additional chemicals to supplement raw diesel fuel [5]. Fuel additives can help reduce emissions caused by less stringent emissions controls and higher mechanical wear inherent to older diesel engines.

In September 2024, the Sulnox Group, an eco-fuel and fuel additive manufacturing company based in London, tested the effectiveness of their flagship product, "SulNOx Eco," which is a diesel fuel conditioner to promising results regarding their claim of lower emissions [6], [7], [8]. The test was conducted in partnership with the Templant Group, a UK-based heavy equipment supplier, which used SulNox Eco on a 100 kilovolt-amp (kVA) diesel generator with a concentration of 1:2000 SulNOx to diesel fuel [6]. The diesel engine used in the generator is an Iveco NEF45 TE2F with EU Stage 3A emissions and no exhaust after-treatment system [9], [10].

Over five weeks, the researchers ran the generator continuously at an 80% load to measure any impact SulNOx Eco had on generator performance, fuel economy, and emissions. The results are summarized in Figure 1 [6].

The exhaust emissions measured in this trial are as follows: Carbon Dioxide (CO_2), Carbon Monoxide (CO), Sulfur Oxides (SOx), Nitrogen Oxides (NOx), and Particulate Matter (unburned hydrocarbon particles) [6].

Particulate matter, also called "soot," is a byproduct of less-than-ideal diesel combustion, comprised of unburned fuel particles, silicates, and sulfates [11]. These particles when suspended in the atmosphere, find their way into the respiratory systems of humans and wildlife. Particulate matter of less than 10 microns, which is smaller than human hair at 50-70 microns, have an easier time infiltrating the lungs of humans and animals leading to headache, dizziness, respiratory illness and cardiovascular illness [3], [11]. If an Exhaust Gas Recirculation system is installed, the soot can be re-introduced into the intake side of the engine leading to carbon buildup with subsequent engine failure. The reductions in PM 10 & 2.5 (particulate matter particle sizes of 10 microns and 2.5 microns, respectively) were measured up to 96 percent with the addition of fuel conditioner [6].

Sulfur oxides (SOx) and Nitrogen oxides (NOx) are generated when the naturally occurring sulfur in diesel fuel, and nitrogen in the atmosphere react with oxygen under high temperatures in the combustion chamber. After entering our atmosphere, SOx and

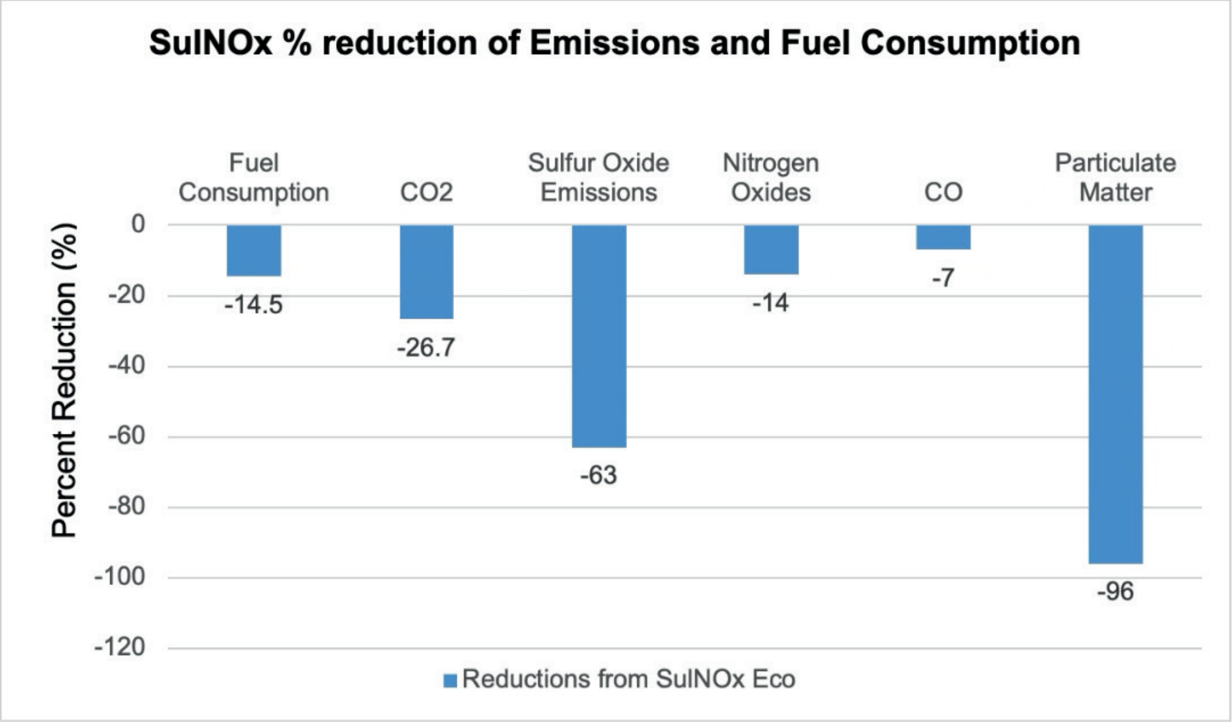

Fig. 1. Percent reduction in Emissions with 1:2000 mixture of Conditioner to Diesel [6]

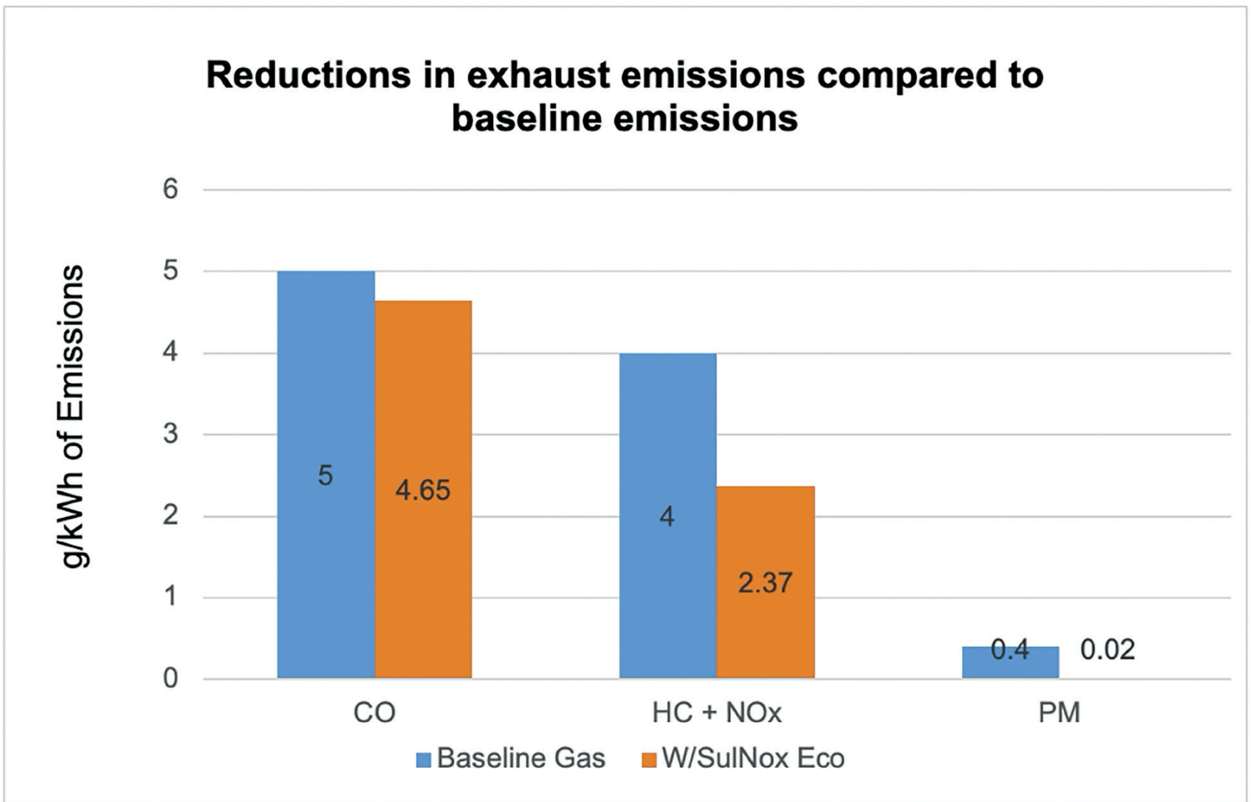

Fig. 2. Comparison between Baseline Emissions (Blue) vs Conditioned Diesel Emissions (Orange)

NOx can combine with water vapor creating sulfuric and nitric acids, aiding in the creation of acid rain [12], [13]. At a pH of ~4.3, acid rain contributes to the degradation of marine ecosystems, damages trees and plants, as well as acid-sensitive, man-made structures like statues and marble [14]. The addition of fuel conditioner contributed to a 63 percent reduction in SOx during diesel combustion along with a 14 percent reduction in NOx [6].

Carbon dioxide (CO_2) is a natural byproduct of fossil fuel combustion and has been present in our atmosphere long before our discovery of fossil fuels [15]. The concentration in our atmosphere increased dramatically within the last 300 years due to increased industrialization (422.8 ppm in 2024) [15], leading to an increase in average global temperatures due to the insulating properties of atmospheric CO_2. The conditioner reduced CO_2 emissions by 26.7 percent [6].

Carbon Monoxide (CO), while not as hazardous to the environment as the aforementioned compounds, still poses danger to human and animal health [16]. CO being a byproduct of incomplete combustion, can cause anemic hypoxia (decreased oxygen in blood) when in an enclosed area, which can be fatal [16]. With the conditioner there was a 6 percent reduction in CO during normal combustion.

Since fuel economy is a function of engine efficiency, the 14.5 percent reduction in fuel consumption can be attributed to the conditioner promoting a more efficient combustion. A more efficient combustion leads to fewer emissions, demonstrated by the 96 percent reduction in particulate matter. Particulate matter is born from incomplete combustion so when more of the available fuel is burned, the engine's overall efficiency increases alongside fuel economy.

Figure 2 compares the emission reductions of SulNOx Eco to the unconditioned output of an EU Stage 3A, Category I engine [17].

The blue bar represents the baseline gas concentrations from an unconditioned engine. CO_2 and NOx reductions were combined, as per EU regulations. The orange bar represents concentration levels if the SulNOx trial conditioner was applied. The EU standards for this engine are 5 g/kWh for CO, 4 g/kWh for HC+NOx, and 0.4 g/kWh for Particulate Matter. The concentrations with the fuel conditioner are 4.65 g/kWh, 2.37 g/kWh, and 0.02 g/kWh for CO, HC+NOx, and PM, respectively [17].

The high upfront cost and long-term maintenance cost of purchasing or retrofitting equipment to comply with emissions requirements can be an unattractive proposition for equipment owners. While not a replacement for emissions control devices, fuel conditioners can fill the niche of a low-cost alternative for costly emissions control devices like Diesel Particulate Filters (DPFs), computer-controlled fuel injection, and Exhaust Gas Recirculation (EGR) systems. For less intensely regulated non-road diesel applications such as generators, construction equipment, agricultural/forestry equipment, and especially older engines without exhaust after-treatment systems, fuel conditioners are a viable, low-cost way to keep emissions down - benefiting human health and the environment while maintaining performance.

Porsche, Karlsruhe Institute of Technology, and Neste's Trial

An alternative solution for reducing emissions is to use bio-mass derived fuels such as renewable diesel. Porsche, the Karlsruhe Institute of Technology (KIT), and renewable diesel manufacturer Neste collaborated in Germany, known as the motherland of diesel fuel, to test the efficacy of "Neste MY Renewable Diesel" against B7 biodiesel fuel in terms of performance, fuel economy and emissions [18], [19]. The study was conducted during a period of three years from 2020 to 2023. Porsche's logistical division supplied trucks and real-world testing grounds for the study [20]. At the end of their trial, the renewable diesel group performed slightly better in fuel consumption with no reduction in engine performance [20].

The experiment uses both renewable diesel and biodiesel in the form of B7 diesel, so distinguishing between both fuels is necessary. Both biodiesel and renewable diesel are biomass-derived fuels. Oils such as canola oil, soybean oil, rapeseed oil, false flax oil, corn oil, and sorghum oil, along with waste fats from food processing, and algae are some of the available feedstocks used in the production of these fuels [21]. However, these fuels differ in their production methods and resultant chemical makeup. Biodiesel uses a process called "transesterification," which uses fats as a feedstock and alcohol as a reactant. Utilizing a basic catalyst yields a separated mixture of fatty acid methyl ester (FAME) biodiesel and glycerin [22], [23]. The resulting biodiesel differs from conventional diesel, as biodiesel contains mostly FAME, lower concentrations of sulfur, and higher oxygen content relative to petroleum based diesel [24]. Renewable diesel, however, follows the same process as traditional diesel [22]. The feedstock reacts with hydrogen and a catalyst under high temperature and pressure until the mixture vaporizes into a mixture of hydrocarbons and water [22]. The hydrocarbons are then sent to a distillation chamber, which further separates them into renewable diesel and other useful hydrocarbons [22]. This process leaves renewable diesel with the same chemical properties as regular diesel, making it suitable as a direct replacement in diesel engines [22].

The B7 biodiesel and the Neste brand renewable diesel were compared using 2 pairs of trucks driving on a combination of highway and urban routes with varying levels of road traffic engine load, and distance [20]. Three public routes were used in the experiment: a 70 km (43.5 mi) highway route, an 85 km (52.8 mi) non-highway route, and a 10 km (6.2 mi) urban route [20]. The 70 km and 85 km routes used two pairs of 40t Scania and MAN trucks with a combination of old and new trucks [20]. One truck used B7 while the other used renewable diesel, and both models were driven in parallel under similar loads on the same route to compare fuel consumption and greenhouse gas emissions [20]. Oil changes were performed every 6 months, with oil samples taken during the change [20].

After three years and a combined one million kilometers (621,400 miles) of driving, the researchers concluded that renewable diesel-filled trucks displayed slightly better fuel consumption compared to the control group as illustrated in Figure 3 [20]. The researchers noted that driver behavior and traffic most likely played an important role in the fuel consumption rates rather than the fuels themselves, as there were more "strong acceleration" events in the control group, consequently leading to higher fuel consumption [20].

To measure exhaust gas concentrations, the group took oil samples every 6 months during the trial, since engine oil can trap gases from the combustion chamber [20]. The differences in fuel dilution, water content, and iron content in the engine oil were determined to be insignificant [20]. The greenhouse gas emissions were comparable to that of ultra-low sulfur diesels with very low soot levels.

After analyzing the results of this trial, it appears renewable diesel is a suitable alternative for conventional diesel. It can also be concluded that the reduction in greenhouse gases is related more to driver behavior rather than fuel type in this specific trial. Conventional diesel uses fossil fuel extraction, which can be a significant source of greenhouse gases. Renewable diesel is derived from plant and animal fats, which seems more sustainable, but requires deforestation and high farmland usage to properly scale up [25]. This process leads to habitat loss and deforestation, releasing more greenhouse gases into the atmosphere [25]. To minimize environmental impact, Neste sourced its feedstock from waste materials like used cooking oil, reportedly reducing greenhouse gas emissions by over 90 percent throughout the fuel's lifecycle [20]. Other sources include animal fat and fish fat from food processing waste, and potential sources from municipal waste and algae [20].

As demonstrated in this trial, the production of the fuel matters as much as the consumption in certain cases. This fact will prove to be increasingly relevant as regulatory bodies begin to account for both production and consumption when drafting regulations in the future. An immediate example of such a regulation is the International Maritime Organization's newly approved Net-Zero Framework [26].

The International Maritime Organization's Net-Zero Framework

The International Maritime Organization (IMO) is a branch of the United Nations concerned with international shipping among 176 participating states [26]. The organization creates standards and legislation agreed upon by member states to ensure safety, security, and sustainability in open water and ports [26]. On the week of April 7, 2025, the IMO approved a plan to reduce greenhouse gas emissions (GHG) by introducing a framework for emissions penalty pricing [26]. This plan is called the "Net-Zero Framework" (NZF) and is poised for implementation in 2027 [27]. This framework will enforce the GHG regulations agreed upon in 2023 by the IMO and targets large diesel ships weighing over 5000 gross tons, which account for 85 percent of GHG emissions in the marine shipping industry [27].

This new framework is an addition to a larger agreement between nations called MARPOL (International Convention for the Prevention of Pollution from Ships), which was adopted in 1973 [27]. Information regarding this framework can be found in Chapter 5 of Annex VI within MARPOL [27].

The NZF is an emissions trading scheme built to incentivize lower emissions from cargo ships. The NZF establishes two tiers of emission targets: the Base Target (Tier 2) and the Direct Compliance Target (Tier 1) [28]. The IMO also established the "Net-Zero fund" to credit ships below Tier 1 and charge ships above Tier 1 [28]. The second goal of this fund is to invest in climate change mitigation projects for small island nations and developing countries [27]. The following is the IMO's plan to properly credit and debit GHG emissions, with a visual aid provided in Figure 4 [28].

- Ships polluting below the Tier 1 target have an emissions deficit (positive compliance balance) and therefore receive "units" or credits from the IMO Net-Zero fund. The units are directly equal to the "positive compliance balance" expressed in Tonnes of CO_{2eq}.
- Ships polluting between the Tier 1 and Tier 2 targets must buy units from the IMO Net-Zero fund.
- Ships polluting over Tier 2 must purchase units from <Tier 1 ships, sell previously banked units, or purchase units from the IMO Net Zero fund priced at a higher Tier 2 rate.
- Until 2030, the pricing for Tier 1 units is "US$100 per tonne of CO_{2eq} on a well-to-wake basis" and Tier 2 units are "US$380 per tonne of CO_{2eq} on a well-to-wake basis". "Well-to-wake" meaning from production to final consumption inside the ship's engine [28].

The targets are measured in percentage reductions of GFI (Global Fuel Intensity), which is a measure of pollution created by a fuel per unit of energy produced [29]. The IMO is measuring GFI on a well-to-wake basis to account for emissions accrued from fuel production to fuel consumption, such that it includes the extraction, processing, distribution, and combustion phases. The percentage reductions of GFI are designed to increase with each passing year from 2028, with Tier 1 percentage reduction

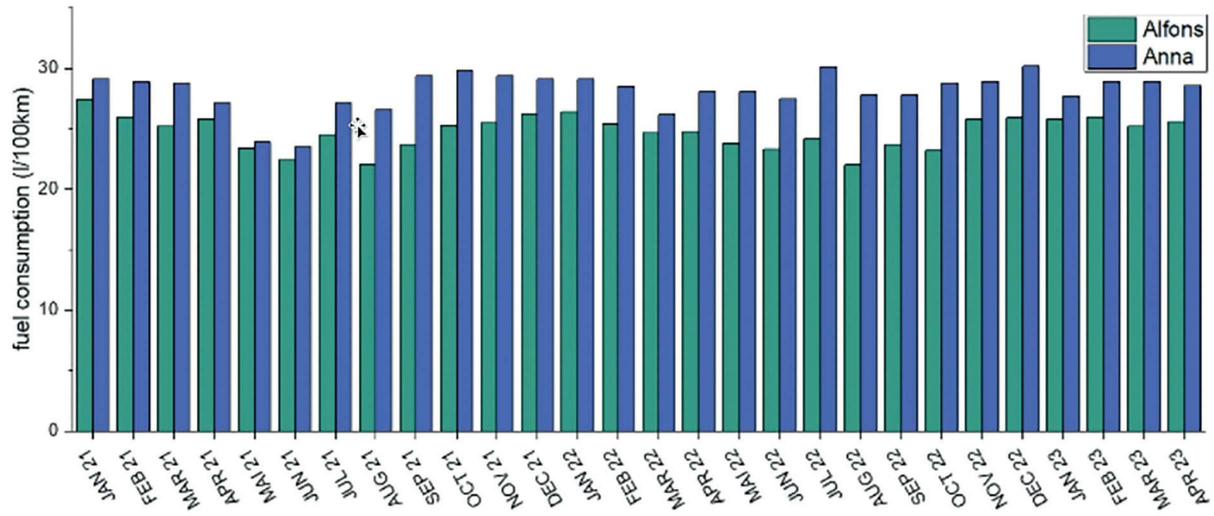

Fig. 3. Comparison of fuel consumption between Neste Renewable diesel and B7 diesel. Green "Alfons" represents Neste Renewable Diesel, Blue "Anna" represents B7 diesel [20].

measuring 17.0 percent and Tier 2 percentage reduction measuring 4.0 percent for the year 2028 [28].

This framework is built to reward ship owners whose ships stay below the GHG emissions target while penalizing ships exceeding the target. By including the well-to-wake criteria in measuring fuel impact, the IMO hopes to steer the shipping industry towards alternative and sustainable fuels to meet Net-Zero standards by 2050. Using the Net-Zero Fund, the IMO plans to use the economics of emissions trading to mitigate the impact of greenhouse gases by investing the fund into "greener" technologies.

The intended impact of this framework depends primarily on the well-to-wake emissions of the fuels used. Biofuels, such as renewable diesel, rely on vast acres of farmland to meet ever-growing demand [25]. The carbon-footprint accrued from clearing land, planting, harvesting, refining, and transporting will all have a significant impact on the well-to-wake analysis of biofuels. This fact was highlighted as a potential consequence of the NZF, bought up by the European Federation for Transport and Environment (T&E) [29]. Since biofuels derived from vegetable oils like palm and soybean are currently the most abundant, the demand for these fuels will increase as adoption of the NZF begins [29]. This may lead to an over-saturation of these fuels in the industry (up to 60 percent), if adequate incentives for renewable fuels like e-fuels, are not made [29]. The IMO's push towards alternative fuels in the near future, makes the future prospects for traditional diesel unlikely in the heavy shipping industry, but if advancements in scalable and sustainable sourcing continue, then renewable diesel can prove to be a solid alternative.

Conclusion

The issue of a fuel source which conforms to stricter regulations along with economic, environmental and user demands will be a recurring theme in the years to follow. Diesel fuel, as well as the industries which produce and consume it, must also conform in equal measure. The petrochemical industry must adapt to this changing climate to better accommodate diesel fuel's evolving role in an increasingly fossil-fuel averse world. With increasing pressure from organizations such as the IMO, traditional diesel technologies are forced to innovate. Biomass-derived diesel like renewable diesel and biodiesel, which offer promising results with little to no effort in translating the fuel to existing frameworks, are the most likely candidates for diesel's eventual metamorphosis. An emphasis must be made on the sustainability and scalability of these new technologies to provide meaningful, net-positive results. Diesel fuel additives are another avenue for users with less stringent requirements. Where traditional diesel fuel lacks in emissions control, fuel additives can help. Fuel additives supplement traditional diesel fuel, acting as an affordable and accessible efficiency booster for aging diesel equipment. These advancements in sourcing, aftermarket fuel conditioners, and legislation are just a small part of an ever-evolving industry, ripe for future innovation, with diesel fuel and the petrochemical industry playing a crucial role in its evolution.

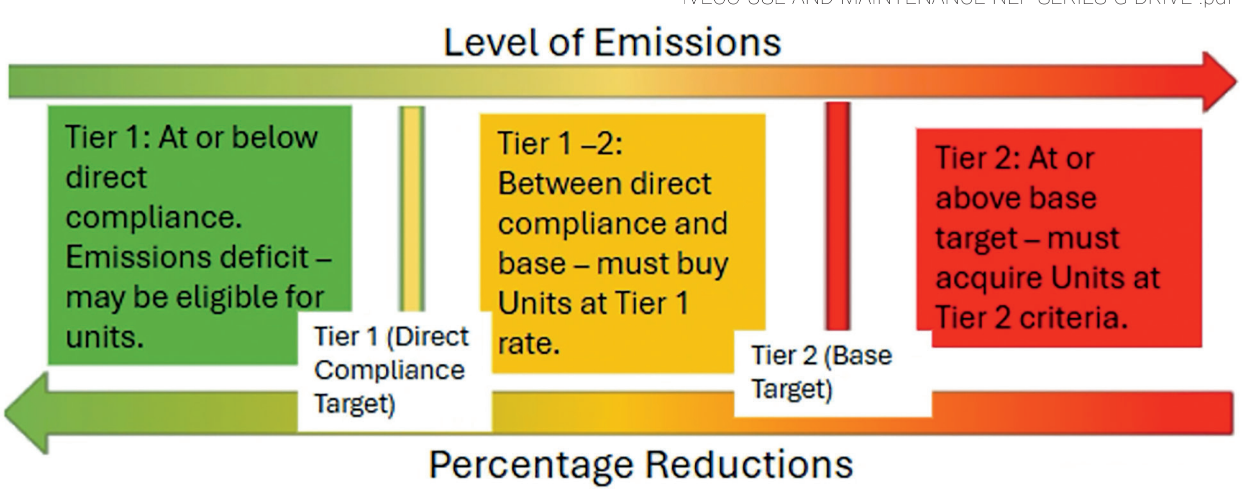

Fig. 4. Infographic on the Net-Zero Framework [26], [27]

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