Alternative Drivetrain for Future Freight Trucks

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ABSTRACT

Presently, heavy-duty trucks are responsible for approximately 25% of global CO₂ emissions. Although the world seems to incline towards the transport sector's electrification, the electrification of long-range freight trucks is profoundly challenging. The dominant disincentives are the required infrastructure, cost/size of batteries, limited mileage, and long charging sessions. However, despite the efforts to reduce emissions, current trends indicate that these continue to rise, mostly because of the continually increasing freight transit. Regional economies are heavily dependent on the latter. Thus, the imminent depletion of fossil fuels and the emerging environmental issues are disquieting aspects for the sustainability of this crucial sector.

This thesis focuses on the possible alternative powertrain/drivetrain solutions for heavy-duty, long-range freight trucks in conjunction with sustainable energy carriers for the transportation sector overall. In terms of viable fuelling alternatives, the following are being reviewed: Electric Power, Bio-Fuels, and Synthetic Fuels, along with their current status, advantages, disadvantages and future prospects.

In terms of powertrain/drivetrain alternatives, the following are being theoretically and critically evaluated and compared against a direct drive conventional Diesel engine truck (25.2% wheel efficiency): Battery Electric, Electric powered with overhead cables or underground conductive coils, combined Gas Turbine/Stirling Engine Hybrid Electric in series, combined Diesel engine/Stirling engine Hybrid Electric in series, and Diesel engine Hybrid Electric in series.

It is concluded that the best scenario for future freight trucks, is the use of an electric drivetrain/powertrain in conjunction with overhead powering cables along the highways. However, due to uncertainties in the universal realization of such infrastructure, to ensure uninterrupted transportation of goods, a plausible transitional solution could be the use of a Diesel engine/Stirling engine Hybrid Electric in series technology. This could reduce emissions/consumption by a factor of 2.4 (60% wheel efficiency). For the case of Gas turbine/Stirling engine and Diesel engine (both) Hybrid Electric in-series arrangements, this factor drops to 1.7 and 1.4 (42.9% and 34.3% wheel efficiency), respectively. Furthermore, this can be a clean and sustainable solution if biofuels are employed as the prime energy carriers. Such an approach is future-proof for use with overhead cables, since the suggested powertrain is electric, rendering a freight truck as a very versatile heavy-duty, long-range vehicle. Electro-fuels are not considered as a viable option due to their inefficient formulation, elevated costs, and problematic handling (Hydrogen).

Keywords:
Future Freight Trucks, Transportation, Sustainable Fuels, Alternative Fuels, Future Mobility, Long Distance Trucks, Hybrid Mobility, Alternative Drivetrain, Electric Trucks.
DISCLAIMER

I, Athanasios Tsamos, hereby declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning. Moreover, I declare that this is solely my own proposal and work.
PREFACE

I would like to thank all the people who supported me mentally during this effort, tolerated me in times of despair, as well as to ask for forgiveness from all the people that I neglected instead of being there for them in times of need!
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1. INTRODUCTION

1.1 Background
Since the beginning of the automotive era in the early 20th century, it is a fact that the ownership of a personal vehicle was sought as a sign of prosperity and power or initially at least, whereas, in the present day, the modern world considers it mostly as a value of individual freedom and as a constitutionally established right. On the contrary, in the undeveloped countries, car ownership is still regarded as a privilege among the wealthy individuals, an established right as well nonetheless or at least in most of them.

Current trends in modern societies are gradually starting to alter our view on this matter towards the more sustainable paradigm of shaping the mobility as a service, a necessity one might say based on current environmental and economic challenges arising from the usage of vehicles. That is, the imminent exhaustion of fossil fuels before the end of the century and the uninterrupted environmental damage caused by the produced green-house exhaust gases. However, life is a vicious circle "walking" side by side with history. Therefore, it would be fair to say that changes in societal and individual behaviors cannot occur drastically within a day or even at least within a decade, for that matter.

The automotive sector is still expanding in both the developed and developing countries. Thus, based on current trends, it is speculated that the present global road travel by all sorts of automotive vehicles, including freight transit, will seemingly double to 80 trillion kilometers in 2050 [1]. Furthermore, automotive mobility inevitably became the most popular and dominant mode of transportation both for persons and goods internationally. According to Van Duin [1], transport and logistics are the key factors for the regional economies as approximately 60% of the regional business is coinciding and depending on automotive transportation. Moreover, with improved logistics and sharing, heading towards the Zero-Empty (car or freight) paradigm, lucrative and productive collaboration in transport logistics can lead to 17% cost reductions according to Muylaert and Stofferis [2]. Increased freight capacities from 55% to 85%, as well as a significant reduction in total CO2 emissions, can be expected with the equivalent analogy of fuel reduction as well. However, in 2010, petroleum-based fuel penetration into the transportation sector was approximately 95% [3]. Hence, it is apparent that even with improved logistics for freight transit management and a radical change in the way we use vehicles individually on an everyday basis, the exhaustion of fossil fuels in conjunction with the latter fact, reveals an alarming scenario for the future. That is the uncontrollable collapse of the transportation sector and the ensuing global economic catastrophe without viable alternative fuels. Consequently, it is crucial to identify and evaluate possible solutions for alternative fueling. At present, from a general point of view, three major possible solutions lie on the table; Electricity, Bio-fuels, and lastly Synthetic fuels, including Hydrogen. Nonetheless, as it seems and with current trends, the transport sector is moving steadily towards full electrification with battery-electric automobiles being most likely the leading adaptation of a clean vehicle of the future. However, the path ahead for heavier vehicles is quite uncertain due to the many hindrances related to their electrification (battery size and cost, mileage, charging time, and overall energy requirements) [4]. This is a crucial aspect. For instance, the German government has set a goal to decrease CO2 emissions in the transport sector by 42% by 2030 compared to
the early 1990 levels. However, it has been observed that the opposite is ensuing due to the increased freight transit and mileage. In the year 2017, this amounted to more than 170 million tonnes of CO$_2$, of which 23.5% were from heavy-duty trucks [5]. In fact, it is estimated that in the EU 20% of greenhouse gas emissions come from freight transit [6].

1.2 Aim
This work aims to identify potential solutions for alternative drivetrains/powertrains for tomorrow’s heavy-duty and long-range freight trucks to reduce or eliminate emissions towards sustainability.

1.3 Approach
This is theoretical research based on the prospects, advantages, and limitations of future energy carriers, current state-of-the-art ensuing technologies of alternative powertrains/drivetrains for such vehicles, and potential novel solutions findings in the literature.
2. METHOD OF APPROACH

This work concentrates initially thoroughly on the potential future alternative energy carriers, as it is crucial to appreciate tomorrow's energy market, prospects, and ambitions. Later on, the state-of-the-art or advancing technologies supporting and/or using the aforementioned future alternative fuels are explored, along with current efforts. Finally, based on the findings from both aspects, possible replacements for the conventional Diesel engines used in long-range freight trucks are suggested. This is a theoretical approach and a critical review of possible solutions. The exact characteristics and specifications (case studies) for individual applications are not the primary concern, which should be part of future work. Sources include papers, journals, and state-of-the-art studies from well-established researchers from the past 10-15 years retrieved from Elsevier, ScienceDirect, ResearchGate databases, and legitimate internet sources.

Keywords used:

3. ALTERNATIVE FUTURE ENERGY CARRIERS

3.1 Electricity

The automotive industry has invested in numerous technologies, some of which have matured enough and hence commercialized. However, they have mostly focused on battery electric vehicles in an attempt to contribute towards the goal of decarbonisation of the transport sector, while maintaining a competitive status.

More specifically, in the last ten years, an upsurge of interest towards the electrification of the transportation sector has been observed. Moreover, substantial incentives have been established, especially in the more developed countries, which led the sales of electric vehicles to rapidly increase from approximately 2 thousand to the impressive 753 thousand annually [7].

This rapid expansion is not expected to be even globally. It is only reasonable to assume that the adoption of electric vehicles will be favored in countries where there will be irrefutable incentives and encouragement as well as in counties and regions where there are already established production industries for the latter, such as: EU, US, CN and JP [7].

Another interesting fact is that the countries with the highest foreseen electrification are the counties with the most visionary renewable energy future strategies and prospects [7].

China, Netherlands, California (US), and Norway are currently leading the way in the direction of full-scale electrification of road transport [1]. New methods to electrify road transport are still being investigated. For instance, various electric distribution heavy vehicles for urban areas are being tested in some cities. Nevertheless, battery-electric freight trucks are not yet plausible due to current technological limitations (mostly battery capacity and charging speed) in conjunction with the required long traveling distances [1]. For private Battery Electric Vehicles (BEVs), a high adaptation and market penetration potential exist as a result of their low life cycle carbon emissions and high well-to-wheel (WTW) efficiency in comparison with the Internal Combustion Engine (ICE) standard cars [8].

Expanding upon that, the dependency on fossil fuels can gradually be alleviated and thus contribute to the reduction of carbon emissions even though in the present day, most of the electric power globally is being produced from fossil fuels. Future power generation will inevitably change direction with the reduction in the availability of fossil fuels, towards more sustainable/renewable or/and nuclear energy sources [9]. Based on the latter facts, ten governments (SE, UK, US, CA, DE, JP, FR, CN, NED and NOR) introduced the Electric Vehicles Initiative (EVI) which suggests a goal for all members of a 30% market share for electric vehicles by the year 2030 [10].

Moreover, apart from the countries mentioned above, numerous other governments, as well as many private companies, have invested both economically and morally towards renouncing the traditional internal combustion engine and the wide adoption of the electric vehicles. Nonetheless, researches reveal that electric vehicle technology is not yet fully
capable of contesting the conventional technology. It is speculated though that with the current rate, both technologies can potentially be rendered equally appealing by the year 2035. Furthermore, it is hypothesized that electric vehicles can secure by 2040 a 12% to 28% share of the global vehicles fleet, which will assuredly lead to heightened global electricity consumption up to 20% [7].

However, despite all the benefits that the electrification of mobility can deliver, profuse limitations and, therefore, challenges exist. There is an ambiguity on the extent to which BEVs are suited as the appropriate replacement of the standard ICE cars as new and/or expansion of the established infrastructure is necessary to meet the required demand for electric power [11]. More specifically, in a study that was carried out by Li and Lenzen [12], it was examined how many electric vehicles the current Australian electricity grid can support, aligned with the quantitatively impact of uncontrolled and controlled charging demand of battery electric vehicles (BEVs) on electric power generation, loss-of-load probability (LOLP), and levelized cost of electricity (LCOE), for both high-fuel-economy and low-fuel-economy (HE and LE) BEVs. For market penetration rates of BEVs ranging from 0 to 100% and controlled charging participation rates 0%, 53%, and 100%, it was concluded that the required charging power causes a rather modest increase in the overall demand by up to 16% and 25% for HE and LE respectively, while assuming a 100% penetration. However, the impact of uncontrolled charging dramatically changed the shape of the demand curve, with the daily peak load being intensified by up to 74% and 92% for HE and LE BEVs, respectively. Assuming a controlled charging strategy with the adoption of smart grid technologies, V2G (Vehicle to Grid) schemes (power being fed from the vehicle back to the power grid if and when required, see: Figure 1) and changes in social behaviors, the peak loads were diminished to an approximate increase of maximum 24%. Nonetheless, the study revealed that even with a precisely controlled charging strategy, the Australian power grid could support HE and LE BEVs with a maximum market penetration of 70%. Things are even worse for uncontrolled charging, with the maximum supported market penetration being at 10%.

In another study conducted by Kintner-Meyer et al. [13], it was concluded that the US power grid’s current infrastructure could potentially support a BEV market penetration of around 73% but only with a controlled charging strategy.

Furthermore, in a study from 2019 [14], the future of electrification in a developing country (Indonesia) was examined, and to what extent the country's current grid, with limited capability of supplying balanced energy, is sufficient for massive penetration of EVs. Certain assumptions were made for this purpose. Firstly, it was assumed that with the current growth, the future number of cars on the Indonesian roads will increase from approximately 9 million (2016) to 15 million in 2030. Secondly, an average, typical charger capacity was set at 3kW with 95% efficiency for the overall charging process (heat losses from battery and transmission wires) and the battery's capacity of the average future EV was assumed to be 24kWh with an average charging and discharging at 50% (half tank analogy). Lastly, two EV market share scenarios were investigated: 5% and 20% as well as V2G charging strategies with participation set at 5, 20, 35, and 50%. The study revealed that especially for a developing country, where the need for electricity will most certainly increase in the following years, as well as because the provision for energy storage is limited (i.e. hydroelectric stations), in order to cope with surges in power demand, there is a
consequential gap between the highest and lowest loads. That has the consequence of significant frequency fluctuations and, most importantly, inefficient operation of the generators. Nonetheless, with the increased employment of V2G strategies, the latter limitations can somewhat be alleviated to some extent but not in the case of a substantial EV market penetration [14].

Based on average electricity consumption data from the Spanish grid between the years 2007 and 2019, Cama-Pinto et al. [16] investigated the maximum number of electric vehicles that can simultaneously fully be recharged from zero to full with average 50kW of maximum charging power in 1-hour intervals and an average battery capacity of 50kWh, across the hours and dates of a whole year. It was concluded that the maximum possible vehicles that can be supported by the Spanish grid are approximately 256,000, but that is the case during the low demand hours in the morning between 2 am and 6 am and only during the colder months of the year. On the other hand, during the hotter months of the year, when extensive use of air conditioning units is observed, especially in the hours between 11 am and 2 pm, interestingly, the grid cannot support any charging operation at all. On average, with current arrangements and installed equipment, it was found that the Spanish grid can support approximately 86,000 EVs charging simultaneously in 1-hour intervals [16].

The associated risks and unequivocal 'spatiotemporally distributed' charging loads, arising from the extensive introduction in the market of a vast number of BEVs, can engender serious obstacles in the path of the stable and economic operation of power systems [12].

This is particularly alarming though, as it is expected that there will be countries where the overall demand for powering their EV fleets will be at least 33% of the overall annual powered generation. In conjunction with the increased renewable energy in the grid and hence rather enhanced unpredictable patterns in power generation, this can potentially lead to disastrous overload in the electricity network as charging habits tend to be at their peak early in the morning or early evening due to the fact that charging is mainly performed at the workplace at the time of arrival or in the afternoon at home after work [7]. However, these charging patterns do not necessarily coincide with the patterns of the peak renewable power generation.
Other potential negative impacts are possible voltage and frequency imbalances, excessive harmonic injection, excess stress on the grid’s electrical components and ultimately possible power disruptions with adverse implications [17].

Therefore, the conversion/upgrade of the electric grid is a matter of great importance due to the rapid expansion of the peak electricity demands from the EVs charging patterns [7].

However, there are certain advantages as well by the extensive penetration of EVs into the grid such as reduced voltage flickering, improved power management with smart controlled charging strategies, frequency regulation, and enhanced renewable energy adoption [17].

Assuming that the current limitations and impediments towards the complete electrification of the transportation sector are surmounted, certain contemporary complications will emerge in the future because of the latter. The abated dependency on fossil fuels will lead to new dependencies and that is the unavoidable reliance on particular, not that abundant, raw materials [18]. Not necessarily limited to, but the paramount of the required raw resources with current technology is undoubtedly the lithium metal [19]. According to Helbig et al. [20], the major challenges can be summarized as follows. Firstly, this metal is exploited in a variety of industries with numerous applications that are continually increasing. Secondly, there are not currently any viable substitutes for the latter. Thirdly, it possesses minimal recycling capability, and in conjunction with its geographically concentrated mining and processing, this leads to a rather elevated economic value. Lastly, there are particular concerns based on its potentially harmful impact on the environment and human health. The amount of the required volumes of lithium will strongly depend on the global number of future electric vehicles but, at the same time, on the average battery capacity installed. Nonetheless and despite the rare nature of this crucial and indispensable metal, Yaksic and Tilton [21], have speculated that there is no serious concern of a potential depletion of required raw materials until at least the end of the century, even with complete electrification of the transportation sector accounting as well the expanding trends of the number for the future vehicle on the streets. Furthermore, at present, only 1% of the global processed and commercialized lithium is recycled, far from the maximum recovery percentage of 80%, which is technologically attainable at the moment, mainly because there are not established structured recycling schemes and rigidly defined strategies for this [22].

Now, in theory, should the extra required electric power and grid capacity issues are subjugated, massive penetration of EVs into the grid can potentially be proven as very beneficial, as they can advance reliability and resilience within the latter, as long as the prominent among the experts within the field Vehicle to Grid (V2G) strategy is employed [23]. However, there are severe burdens with such an approach. The inescapable battery degradation from the enhanced bidirectional charging is a sincere concern in conjunction with the, somewhat, problematic cost and supply of lithium batteries, and the potential warranty issues for the consumers [24].

But, a V2G strategy apart from the contribution in the stability of the electrical grid can be proven as a favorable stream of revenue for the vehicle’s owner for providing these regularization services. Shinzaki et al. [25] predicted in their research that these services could bring in a revenue somewhere in between 600$ and 1,000$ annually, whereas
Kempton and Tomić [26], estimated that these revenues can be as high as 2,500$ per year. Thus, outweighing the adversary effects of the intense cycling loading on the battery packs are. Nevertheless, it should be mentioned that these numbers are just speculations since the future market can have unpredictable economic patterns and new policies that will be formulated and affected by multiple players.

Battery degradation, warranty, and range anxiety (battery capacity, charging time and duration) are some of the most critical challenges that need to be tacked apart from the grid capacity and stability in order to proceed in a constructive manner towards global electrification, or at least only for the private commercial vehicles. V2G strategies can tackle some of the aforementioned problems, but not all. Therefore, perhaps another approach is not necessarily such a scheme as this requires a radical change in the habits and way of thinking for the average population but rather the localized installation of energy storage provisions, which can eliminate the exploitation of individual vehicles as stabilizing factors. More specifically, in 2017, the American Electric Power company initiated an ambitious project, investigating the effects of installing a 2MW battery in a local substation transformer [24]. This had a comparable effect as managing a fleet of EVs via a V2G strategy. Furthermore, it was shown that this could be proven as an effective method to reduce stress on a national grid as storage can be concentrated locally and, therefore, promote free charging patterns and alleviating some of the owners’ concerns.

3.2 Biofuels
Besides electricity, other potential alternative automotive fuels of the future are the biofuels. Notably, the most common biofuels are the Bio-Ethanol and Bio-Diesel currently made out of feedstocks like starchy & sugar crops (sugarcane, wheat, corn, barley, Etc.) and plant-based fats (rapeseed oil, soybean oil, sunflower oil, Etc.) respectively [27]. The dominant feedstocks in the EU are rye, wheat, corn, barley, rapeseed oil, soybean oil, and sunflower oil [3]. Currently, ethanol produced from vegetables and other bio-sources is possibly the cleanest form of biofuel [28].

With the imminent exhaustion of fossil fuels, the accelerating demand for fuel in the transport sector, the environmental concerns, as well as the insecurity of a constant supply of petroleum from politically unstable regions of the world, has resulted in considering these fuels as very promising and viable alternatives [3]. However, their current commercial value is much higher than their petroleum-based equivalents. However, with the perpetual price increase of petroleum, it is estimated that they will become very competitive by 2030 [29]. Governments have established quotas, policies, and tax exemptions to alleviate the price difference between them and promote their use as a sustainable, eco-friendly alternative [30]. Moreover, various countries have introduced specific mandates aiming towards the replacement of traditional fuels by biofuels or at least a meaningful percentage of them. For instance, EU has the aspiration to reach a 10% bio-energy share in the transportation sector by 2020. On the other hand, the 2007 Energy Independence and Security Act (EISAct 2007) in the US, impose the use of 36 billion biofuel gallons by 2022 [31].
Still, despite all the efforts, the market penetration of these sustainable fuels is comparatively limited. At the moment, only Brazil is able to produce market competitive bio-ethanol (cost-wise). More specifically, in 2007, the highest market share of biofuels was observed in Brazil with 20% penetration, while in the US and the EU these percentages were as low as 3% and 2% respectively [3]. By far, the most prevalent, production-wise, sustainable biofuel is bio-ethanol. In 2011 the production globally reached approximately the number of 545 million barrels, while for bio-diesel, the production was some 147 million barrels. In terms of quantity, the major producers were the US (61%) and Brazil (26%), (rest of the world: 13%). On the other hand, in 2011 EU was the leading producer of bio-diesel (44%) followed by the US (16%) and Brazil (11%), (rest of the world: 29%) [31].

As mentioned earlier, although biofuels are expected to equalize in terms of cost with fossil fuels in the following years, the global production compared to the global demand is minuscule as the current global market share for these sustainable fuels indicates. There is a legitimate reason behind this. The 1st generation of biofuels is obtained/formed from feedstocks used directly in food production (corn, wheat, sugarcane, plant oils, etc.) and therefore compete directly or indirectly with the available food for the population [27]. That can lead to a severe price increase for global food and consequently affect food supply, especially in emerging and developing countries or regions with high population density, such as the EU countries, where the arable land is definite [32].

Various studies have thoroughly examined the relation between bio-fuel production and food price. Notably, in 2010 Roberts and Schlenker [33] concluded that the US biofuel mandates could render the available food 30% more expensive with the prospect to level at 20% if one-third of the bio-fuel calories are recycled as feedstock for livestock. Furthermore, Baier et al. [34] appraised that the global price increase of corn, soybean, and sugar between the years 2006 and 2008 was 27%, 21%, and 12%, respectively, with the overall global food price increase being approximately 12%. In another study, it was estimated that the worldwide increase in the food price index in 2007-2008 was approximately 19%, as a direct consequence of the global bio-fuel fabrication [31]. Thus, a lot of effort and money has been put into the 2nd generation of biofuels where novel cellulosic feedstocks are being employed, such as wood residues, whole plants, trees, and bio-waste to produce bio-ethanol and bio-diesel [3]. However, current cellulosic conversion technologies are not very efficient, thus are rather expensive, and therefore the annual global amount produced is extremely limited [27]. Nevertheless, in the following years, it is expected that along with the 1st generation of bio-fuels, their prices will favorably augment and level down with the prices of the latter [29].

Now, it is a fact that these 2nd generation sustainable fuels are promising and do not compete directly with food sources. However, they utilize plant matter that consumes arable land in order to be grown and, therefore, although indirectly and to a lesser degree, they still occupy useful land that could have been exploited for food production [31]. Perhaps the most promising of them all is the so-called 3rd generation biofuels derived from algae that foremostly do not necessarily occupy arable land [31].

Algae are photosynthetic organisms that grow in diverse aquatic environments and can withstand various habitat conditions, including different salinities, varying temperatures, and light intensities, different pH levels, as well as they can tolerate other organisms in a
symbiotic regime. All the above are rendering them capable of flourishing in water reservoirs and even desserts [35]. To a great extent, they possess the ability to convert atmospheric CO2 into useful products. Therefore, they bear the prospect of becoming sustainable, renewable, and possibly efficient raw materials for industrial bio-fuel formulation. Algae are rich in, but not limited to, polysaccharides and lipids, among other compounds, which are of direct interest for bio-ethanol and bio-diesel production, respectively [36]. It has been identified that they are superior in terms of the quantity of oil produced than the oil extracted from traditional agricultural crops [37]. These microorganisms have the potential to yield better quantities of biofuel overall, not just oil or biodiesel, but rather bio-alcohols as well. Notably, bio-ethanol and bio-butanol are typical examples with the potential to replace traditional jet fuels [37]. Nonetheless, with the current technology, certain impediments exist, such as enhancing the microalgae growth, dewatering algae culture efficiently, the pre-treatment of the biomass, and the optimization of the fermentation process [38]. The steps and techniques in biofuel production from algae are summarized in Figure 2, below.

![Figure 2 - Steps and techniques involved in biofuel production using Algae cultures, in [37].](image-url)

The shipping sector is typically dominated by slow-burning fossil fuels. Oil-based biofuels are considered as an excellent replacement for the current slow revving diesel engines that most of the current bulkier vessels are equipped with. Furthermore, sulfur content and the latter’s consequential emissions are a matter of great importance as well. It is a fact that within these alternative fuels, the sulfur content is shallow if not non-existent [39]. More specifically, for the most cumbersome and slowest revving marine engines as a replacement for heavy fuel oil (HFO), straight vegetable oil (SVO) seems like a potential substitute. Bio-diesel is considered a promising alternative for the case of medium-sized/revving marine
engines as a replacement for marine diesel oil (MDO). Finally, for the smallest high revving, marine engines typically used in fast boats and pleasure crafts, liquefied biogas, and/or bio-ethanol seem viable options [39].

Several major players within the marine engines manufacturing sector have already tested and implemented biofuels in their engines. The Finnish Wärtsilä Corporation back in 2001, tested a variety of oils as fueling options (palm oil and olive oil among others) on a stationary Wärtsilä 6L32 marine engine with promising results. Moreover, in 2003 the company successfully manufactured its first power plant employing biodiesel in Germany [40]. Other companies in the field followed this initiative. Notably, MAN Diesel Company evaluated favorably its novel 2-stroke low rpm engine combusting bio-oil solely. Furthermore, in the following year, the same corporation tested additionally another novel 4-stroke medium revving arrangement combusting palm-oil derived biodiesel with success [40]. Another example is Caterpillar Incorporated (US), which declares that their current consortium of marine engines can employ up 30% of biofuel within the conventional fuel mix without further modifications [39].

Certain advantages can unravel current concerns of fossil fuel usage with the extensive use of biofuels in the marine industry. These are increased combustion efficiency and higher cetane number, low sulfuric content, low aromatic content, and of course, renewability. On the other hand, broad technological integration and, most importantly, availability, for all the reasons mentioned earlier, are primary obstacles nevertheless [40]. Biofuels derived from vegetable-based fats suffer from another complication as well. The reducing fluidity and crystallization at lower temperatures is an issue as well, especially for vessels sailing in colder regions of the planet [41].

Although the prospect of wide adoption of biofuels in the energy mix market seems auspicious, the dominant impediment at the moment is most definitely the current cost. For instance, the price of biodiesel in the US is considerably higher compared to the price of conventional diesel. That is $3.51/gallon and $2.61/gallon respectively (Apr 2020) [42]. The final cost is mostly dependent on the price of the raw materials required, which can reach 60% to 75% of the total cost, and not that much on the additionally required synthesis processes [39]. Furthermore, as raw materials cost fluctuates, depending on the grown/produced region, it is only reasonable that the cost of biofuels varies significantly across different countries and regions [39].

Another crucial aspect of biofuels is their potential use in gas turbines for power generation and aviation. Various studies revealed that their exploitation in the more robust ground gas turbines could be achieved with minimal modifications to the existing technology. However, in aviation, there are more scrupulous statutes and standards regarding jet fuels. A fascinating application of biofuels is perhaps their use as a fuel in the relatively recently developed micro- gas turbine (MGTs) units. Many studies have been undertaken regarding this matter [43], [44], [45]. All these researches proved that biodiesel is an acceptable replacement of conventional diesel, for use in gas turbines that combust the latter in atomized form. Nevertheless, significant variations and contradictions were recorded in terms of emissions. More specifically, high NOx emissions were reported in [43], whereas in
[44], the opposite occurred, with emission reductions ranging between 14% and 60% based on the thermal input in the turbine. The viscosity and chemical properties of biodiesel from distinct raw materials affect the droplet size emerging from the injection atomization process. Larger droplets result in slower combustion rate and lower primary zone flame temperature, thus higher emissions (both CO and NOx) due to less efficient and incomplete combustion (typically conventional diesel is a thinner fuel), [45]. But, it should be mentioned that a sufficiently small droplet size (higher atomizer operating pressure), resulted in favorable outcomes compared to diesel, which can mostly be attributed to the extra oxygen present in biodiesel's chemical composition, promoting a leaner and more complete combustion process [46]. Compared to other forms of biofuels, biodiesel with extra oxygen content and satisfactory atomization can result in diminished exhaust smoke, reduced harmful emissions, and minimal engine deposits (soot) with equivalent performance to conventional fuels. One disadvantage, however, is the latter's somewhat lower calorific content because of the reduced carbon content [47], [48].

Generally speaking, biodiesel and other forms of bio-oils are potent replacements of conventional fuels in turbine units, despite their typically lower energy content, with minor modifications to the fuel delivery system (improved atomizer, preheat to avoid crystallization of the fuel in colder conditions). Contrastingly, bioethanol, which is another appropriate but less common fuel for gas turbines, requires extent modifications to the fuel delivery system due to its lower flash point, lower viscosity as well as its high vapor pressure [49].

### 3.3 Electro-Fuels & Hydrogen

Besides Electricity and Biofuels, Electro-fuels (or synthetic fuels) are carbon-based fuels formulated from CO2 and water, with the electricity being the fundamental source of energy typically by mixing hydrogen derived from electrolysis and CO2 in a reactor, composing these energy carriers. A variety of liquid and gaseous fuels can be engineered, notably: methane, methanol, gasoline (petrol) and diesel [50]. The resulting by-products consisting of pure oxygen and heat out of this process can be quite valuable as leverage revenues that can potentially reduce production costs by approximately 10% [51]. Electro-fuels are possibly a promising method to exploit the increasing renewable energy percentage into the energy system, by exploiting the excess (or exclusively) generated electric power for electrolysis purposes in order to produce hydrogen gas. Nevertheless, this requires new infrastructure, which can be costly [52], [53]. The hydrogen gas can be employed later on either as a standalone fuel (after liquefaction) or used for power generation. Currently, the largest percentage of global hydrogen production is acquired from processing fossil fuels, and only a small percentage is from the electrolysis of water, which is a rather expensive process due to high initial capital and running costs [54]. A summary of all the steps involved in the production of Electro-fuels is illustrated in Figure 3.

Numerous factors affect the final price of synthetic fuels. Depending on the type of electrofuel and its complexity, from the elementary hydrogen gas to liquid high-carbon-content complex fuels, the most important factor contributing towards the final price is the cost of
hydrogen production which is consequently immensely dependent on the electricity cost required for the electrolysis process [56], [57].

Note that hydrogen extraction from fossil fuels through thermochemical processes is not considered an option because these methods are not renewable and, therefore, not sustainable. Furthermore, hydrogen produced from the processing of organic biomass feedstock is not a consideration as well, as this lies with biofuels and not electro-fuels. The second most important factor affecting the final price is the initial capital cost, which is more conspicuous in low capacity installations [56]. Notably, the electrolyser’s capital cost, with efficiencies ranging between 40% and 70%, can be as high as 50% of the total capital investment required, followed by the fuel synthesis capital cost, the CO2 extraction equipment capital cost [55]. The final capital cost incorporating all the factors mentioned above can lie between 500 €/kW_fuel to 10,000 €/kW_fuel capacity [55], depending on plant’s size and intended fuel type synthesis. By accounting all the above parameters, the synthetic fuels production costs ranged from 0.20 €/kWh_fuel to 0.28 €/kW_fuel in 2015 whereas it is estimated that these costs will diminish to the range of 0.16 €/kW_fuel to 0.21 €/kW_fuel in 2030, which is still more expensive compared to biofuel prices future trends [55]. These costs refer only to production costs, and they exclude any handling, storage, and distribution tariffs. The latter can potentially add-up significantly to the final consumer price rendering the liquid synthetic fuels more cost-efficient compared to gaseous synthetic fuels due to the significantly lower associated handling and distribution costs (requiring no liquefaction), regardless of the increased production costs [55]. For instance, in the case of gaseous synthetic fuels, liquefaction is required as a prerequisite for fuel distribution. Hydrogen is a peculiar case though, as special infrastructure is required for both its

Figure 3 - Production of Electro-fuels, in [55].
liquefaction and its safe and unproblematic distribution. This matter will be analysed to a greater extent later on in the following sentences. Nevertheless, expanding on the production costs but this time with distribution costs included, the average (household) selling price of natural gas (which is consisted mostly of fossil methane gas among others) is 0.06 €/kW_fuel (Germany, 2020), [58]. On the other hand, the average production cost only of synthetic methane is approximately 0.20 €/kW_fuel, which is considerably higher [55]. Interestingly, and excluding hydrogen, methane is the least expensive synthetic fuel to produce [55]. For more compound liquid fuels, such as synthetic methanol (which can be used as a combustible substitute of gasoline or ethanol), the production cost only is approximately 0.25 €/kW_fuel [55]. The conventional gasoline and bioethanol production costs (in US, 2017) were approximately 0.05 €/kW_fuel and 0.09 €/kW_fuel, respectively (handling, distribution, taxes, and sales profits are excluded), [59]. Thus it is apparent that overall synthetic fuels are not comparable at all cost-wise with their competing equivalent biofuels.

Now, it is a fact that the least expensive, not carbon-based, synthetic fuel is by far the standalone hydrogen since there is no need for investments in CO2 extraction process equipment and mixing reactor. In addition, the extra energy input required in order to compose a more chemically complex fuel is rendered obsolete. As a result, the production cost of pure hydrogen from electrolytic processes is settled on average approximately 0.13 €/kW_fuel [60], (depending on the electricity input source) compared to an average of the next least expensive electro-methane at 0.17 €/kW_fuel [61]. This production cost (of pure hydrogen) can be halved in the special case that a nuclear energy source is employed [60]. Of course, the latter is not a renewable energy source, but under certain conditions, it can be considered as a clean form and practically 'endless' (at present at least) energy source.

As a gas, hydrogen requires liquefaction in order to be distributed or stored. Since from a molecular point of view, it is the simplest gas found in nature (the intermolecular van der Walls forces are meager). This has as a consequence of a very low liquefaction temperature of -253°C at atmospheric pressure. In real-life applications and not within a lab, this temperature is practically impossible to be achieved meaningfully for bulk quantities of hydrogen production. Thus substantial pressure is required in conjunction with meaningful cooling for a liquefaction process. The energy requirements of such a procedure can be as high as 30% of the energy content of the liquefied fuel [62]. This is not a negligible percentage. Moreover, the conventional established infrastructure for storing and transporting liquefied gaseous energy carriers is not applicable to the case of hydrogen. More specifically, due to this particular gas’s volatile nature, the conventional sealants of the pipes and pumps between the armaments are rendered inoperative. Furthermore, hydrogen embrittlement is a phenomenon arising in metallic structures in which hydrogen is stored or being transferred. This refers to a form of microstructural damage arising from the development of porosity in the metallic microstructure. This leads to the subsequent corrosion of the structural material as a consequence of the exceedingly volatile and minuscule hydrogen molecules that can gradually penetrate through the latter [63], [64]. Appropriate materials for this purpose are metal hydrides (Metal hydrides constitute a class of chemical entities in which hydrogen is chemically bonded to the metal centre) or carbon fibre composites. However, all these come at a cost, and hence the establishment of new
networks incorporating these materials is rather cumbersome due to the prohibitive cost of such a project [63]. Another serious concern is safety. Storage must be kept at reasonably low temperatures to avoid possible leakages and potential accidents because of the immense pressure employed in order for the gas to be maintained in liquid form [63].

Despite all the negatives, hydrogen can be combusted as usual with minor modifications in conventional IC engines with approximately 40% thermodynamic efficiency, but perhaps the most compelling application is within fuel cells that generate electricity through a reverse electrolysis process with conversion efficiencies exceeding 80% [53]. Although the inauguration of novel networks for the distribution of hydrogen is quite ambitious and most certainly burdensome, the local storage near renewable power plants seems very appealing as backup on-demand energy storage if coupled with fuel cells instead of using other more complex forms of electro fuels. The former requires some form of thermodynamic process (Brayton cycle, Rankine cycle, or combined cycles) in order to produce electricity. It is a fact that even the most efficient current conventional power plants do not reach the 80% electrical efficiency of the hydrogen fuel cells.
4. STATE-OF-THE-ART ALTERNATIVE TECHNOLOGIES FOR LONG-RANGE TRUCKS

With current trends, it seems that the global transportation sector is moving towards electrification or at least for private automobiles. Indeed, automotive manufacturers have invested many funds initially in Hybrid Electric/ICE vehicles, and at present, they are gradually starting to present and sell full battery electric vehicles. Although hydrogen (as a combustible or as an energy carrier for use in fuel cells), is another eco-friendly with zero emissions alternative, the many hindrances in its distribution and storage seem to prevent its wide adoption. Nonetheless, there are examples where it has been employed instead of electricity. The other viable option is to employ biofuels or electro fuels as combustibles in conventional internal combustion engines. This section deals with current technologies supporting alternative energy carriers for heavy-duty and long-range vehicles (trucks, lorries, etc.)

Following the trends of privately owned cars, electrification, which is a rather mature technology, is considered an option for these vehicles (heavy-duty trucks). However, as it was mentioned earlier, there are specific problems regarding this approach. The main obstacles are firstly the mass/volume and hence the cost of the battery in order to meet the traveling distance requirements [65], [66]. Secondly, the necessary charging network for such vehicles, in comparison with smaller automobiles, is exceedingly expensive to establish [65]. Lastly, because of the enormous energy requirements and thus, the vital large battery capacity needed, charging speed/time is an obstacle as well [66].

There are various suggestions to overcome some of these problems. The most obvious solution is perhaps the overnight (before the trip) charging of the trucks in a (company's) depot [67]. This approach limits the truck range to its maximum range of 1 charge, as set by the vehicle’s manufacturer. Therefore, the destination must be at a distance of less than half of the maximum range (half of the trip is at the destination, and the other half is the return route). For instance, the Tesla semi (see: Figure 4) which has four independent motors on rear axles, a 480 Km range, and approximately 2 kWh/Km of consumption [68], would require at least an 80 kW charger to charge the battery pack with a reasonable safe pace (ensuring its longevity) in 12 hours [67]. Thus, it is apparent that this approach does not allow any room for international freight travel even with the 800 Km range [68] version of the latter. Moreover, there are many (large) countries (i.e., US, Germany, China, Russia, Canada, India, Etc.) with massive highway networks, and therefore a limitation for domestic freight distribution arises as well. Apart from Tesla Inc., other manufacturers of such vehicles are the Swedish SCANIA AB, which has deployed battery electric trucks in Norway (27 tonnes, 120 Km range) [69], MAN with its MAN TGM 26.360 E electric distribution truck (18-26 tonnes, 190-200 Km range) [70], and others.
Another approach is the opportunity charging. This method suggests the battery's partial or full charging during the driver's resting periods or during loading and unloading of the goods [71]. As expected, such an approach does not allow long charging sessions, but on the other hand, less bulky batteries can be employed, lowering the ownership cost. As a major disadvantage, numerous specialized fast-charging stations are required across the highway to ensure unproblematic charging access for the truck drivers, a very ambitious and costly concept nonetheless. Furthermore, certain freight companies employ two drivers for the same truck in order to eliminate the time losses from the compulsory by law resting periods. Obviously, opportunity charging is not applicable in this particular case. Another limitation is perhaps in the case of international freight transport as certainly required infrastructure might not be present in transit or final destination countries. This scenario, however, is currently being tested with excellent results in local freight distribution services (not necessarily limited to heavy-duty vehicles) from parcel/postal delivery companies such as DHL [72], FedEx [73], and various municipal bus services mainly in China and India [74].

Lastly, the uncontrolled on-demand charging would require all the currently existing refueling spots to possess the capability of massive, fast charging of trucks, which, from an infrastructure's cost point of view it is cumbersome and thus prohibitive. For instance, according to Earl et al. [75], if it is assumed that somewhere between 5 to 50 trucks are being charged simultaneously, this would require 1.5 MW to 20 MW of power, a massive number by all means.

Perhaps, from the electrification of the road freight transit point of view, the most promising solution is the E-highways concept by Siemens and Scania [4]. In such an approach, the electricity required to power up the trucks is provided by overhead power lines similar to those employed by trams or electric trains (see: Figure 5), in conjunction with smart metering and billing services. Such schemes are currently being evaluated experimentally.
with success in Germany, in Sweden, and in California in partnership with Volvo and Scania. Another similar approach is the use of inductive coils below the tarmac for a contactless charging scheme, although the latter raises health issues associated with the intense electromagnetic radiation generated in order for this to be achievable [76]. According to Ambel [4], both these methods have the potential to electrify by 2050 40% to 60% of all highway trucks. The main advantages are the high efficiency, flexibility, and more affordable cost for the vehicle as a limited battery is required for energy storage. Furthermore, to an extent, infrastructure's capital cost is reduced as well, since there is no need to electrify all parts of the highway, assuming, of course, that there is an on-board battery provision.

![Image: e-Highway Concept](image_url)

**Figure 5 - The e-Highway Concept, [77].**

To a lesser extent, instead of employing electricity directly as the energy carrier, hydrogen coupled with fuel cells has been suggested as a possible solution. However, according to Ambel [4], in order to be considered as a sustainable solution, the latter must be produced by employing renewable energy sources. Moreover, fuel cells possess elevated capital costs, and therefore this is a rather expensive technology. High refueling network infrastructure cost is another drawback, as it was described in the previous section. Lastly, this approach is approximately three times less efficient in comparison with employing electricity, as is directly [4]. Indeed, as it was presented earlier, hydrogen fuel cells are roughly 80% efficient. Considering that with current technologies electrolysis is at the most 70% efficient and for liquefaction 30% of the hydrogen’s energy content is consumed, (this leading to a liquefaction efficiency of 70%,) this leads to a 0.7x0.7x0.8 = 0.39 (~ 39% efficiency) utmost, thus supporting the one-third efficiency stated previously. Despite these facts, there are examples of such trials. For instance, a US company named Nikola Corp. announced that it will commence the manufacturing of hydrogen trucks in 2020, such as the Nikola One (1200 Km range, refill in just 15 mins.) [78], [79].
Finally, the last scenario is rather straightforward. That is the wide adoption of Synthetic Fuels (Electro-fuels) or Bio-fuels while maintaining the conventional internal combustion engine as the powertrain instead of replacing it with electric one [75]. Of course, this would require massive production volumes, which is currently not the case, as it was seen in previous sections.
5. PROPOSED ALTERNATIVE DRIVETRAIN FOR LONG-RANGE TRUCKS

In the previous sections, the possible alternative energy carriers of the future were explored, as well as the current efforts for long-range freight trucks employing some of the latter were presented as well. This section aims to investigate and assess novel possible solutions on top of the currently established trials, efforts, and suggestions. In order to proceed with this, the establishment of a recapping framework is deemed necessary. Firstly, it was deduced that electricity is the most efficient energy carrier compared to synthetic fuels, including hydrogen, since substantial energy amounts are required (electricity) for their synthesis, processes that involve particular efficiencies, and thus a reduced Well-To-Wheel efficiency is observed. Battery electric trucks have high purchase cost due to the cost of the massive batteries required. Other disadvantages are the limited applicability for long-range transits, as well as the long charging times required. It is considered though that this could be an excellent approach for specific vehicle types in urban areas, such as garbage trucks, postal trucks, and busses. Probably, the best solution towards the electrification of long-range trucks is the E-Highways approach, a less complicated proposition by all means (lower capitals required both for the involved infrastructure and vehicle costs). However, it should be noted that until an international adoption of such technology becomes a realization, international and probably cross-country freight transit is not possible with this method. On the other hand, hydrogen, coupled with fuel cells and an electrical powertrain/drivetrain, can alleviate these problems. Handling and distribution of hydrogen, however, is precarious. Furthermore, it directly competes with renewable electricity (required for its synthesis via electrolysis) that otherwise could have been distributed and consumed more efficiently in the grid directly. In terms of energy carriers, though, the 3rd generation of biofuels seems to be very promising as they do not compete with electricity produced from renewables. Current suggestions dictate that they could be employed in conventional IC engines without the need for altering/swapping technologies. However, with limited production volumes, they will probably have to compete with fuels required in the shipping and aviation sectors. Within an urban area, due to zero-emission future policies, mandates, and quotas that will gradually be administered, this approach has assuredly no future [4]. Nevertheless, these restrictions are unlikely to be adopted in rural areas if employed fuels are renewable (i.e., biofuels).

Now, internal combustion engines are quite inefficient, though, thus it is suggested that a scaled-down combined power plant similar to major operating power plants producing electricity could be a solution until the full adoption of E-Highways. Such a setup could be coupled with the readily available and relatively mature electric powertrain technologies and a small volume battery pack (reduced vehicle cost), as an in-series hybrid arrangement [80]. This will provide the necessary power boost during rapid acceleration or provide a certain mileage for the occasions when the trucks have to travel through urban areas. Furthermore, this could be an all-inclusive solution, as the use of overhead cables or individual charging is not prohibited, due to the existing electrical equipment on the vehicle. Lastly, another advantage is that it can be employed with current fossil fuels while eliminating the...
conventional diesel engines with the potential to drop greenhouse gasses and pollutants dramatically. A direct drive arrangement is not considered as an option, due to instant power output and efficiency limitations. In Figure 6, the differences between the “classic” in-parallel and the suggested in-series hybrid electric arrangements are illustrated.

Within this framework, combinations of Brayton-(gas turbine)/Stirling-Engine, Conventional-IC-Engine/Stirling-Engine cycles, and a standalone diesel reciprocating engine coupled with a generator, are explored with state of the art information retrieved from the literature. Combinations of the above with a Rankine cycle are not considered viable options due to the many technical difficulties related to the required equipment for cooling. This is not a detailed technical review but rather a critical and theoretical investigation on whether such an approach is viable, based on all the information given in the previous sections. This though, does not apply to efficiency, which is the primary interest and therefore, will be used as an evaluation measure and comparative factor for the different arrangements. Moreover, the exact energy output of these configurations is not a concern here, as it is assumed that these can be scaled accordingly in order to meet demand. The advancements in Microturbine Generators mentioned in the biofuels section give enough confidence that this concept is feasible in terms of both output capacity and scales.

Abdulrazzak and Eiad [81] performed a comparative energy analysis on a combined power plant consisting of a gas turbine and a Stirling engine while accounting for the various individual components’ ensuing efficiencies. They reported that brake efficiencies of more than 50% could be achieved, subject, however, to an appropriate compressor pressure, exhaust temperature, and air/fuel ratio. Bolland, in [82], reported similar results. Since the intention for this power plant is to be coupled with a generator and not arranged as a direct drive, the identified 'sweet spot' operating conditions could be maintained at all times at their primes. Thus a constant efficiency could be achieved, something that was not mentioned in the above studies.

For the case of a hot air cycle and Diesel engine combination, Patton and Bennett [83] suggested a very interesting design, coupling a Diesel cycle with a Stirling engine as an integrated and combined robust arrangement (not in series but as a single combined system). Their suggestion is as follows. A regenerator is positioned between the intake/compression cylinder and the power/exhaust cylinder, acting essentially as a heat exchanger that absorbs/saves heat during exhaust. This heat is then released on the next cycle where compressed intake gasses, flowing in the opposite direction, absorb the latter before the power cycle. With this approach, it was evaluated that brake efficiencies exceeding 70% can be achieved. The principal reported disadvantage was the relatively low power density arising from lowered volumetric efficiency (thus low power) due to the low compression ratio, late air intake, and late combustion. This, of course, was reported as an issue for a direct drive setup where an engine is operated across the whole rpm range. Again and for the same reasons described earlier, running this engine in series with a generator and an electric drive, supported by a battery pack and a management system, can result in peak efficiencies at all times eliminating the aforementioned limitation of this proposal.
Finally, a standalone conventional low/mid rpm Diesel engine typically used in heavy-duty trucks and marine vessels have approximately with current technology about 40% [84], [85] thermal efficiency. As a direct drive, accounting for the losses of the drivetrain as well which can be as high as an additional 15% (63% efficiency approximately) [86], the overall efficiency effectively drops to around 25%. This means that only this percentage of the chemical energy within the combustible fuel is converted into useful mechanical energy (the rest is mostly lost as heat).

A hybrid in series arrangement where an engine drives a generator producing electricity, which subsequently is used to charge an auxiliary battery and/or set in motion an electrical powertrain eliminates these drivetrain losses [80]. There are certain efficiency losses as well with this method, but these are inconsequential. More specifically, the efficiency of a well-designed electrical powertrain is typically around 90% - 95% (this applies to generators as well). The same efficiency is ensuing in modern electrical motor controllers and management units. Normal charging and discharging of batteries with reasonable charging power can be somewhere in between 90% - 95% efficient as well [75], [80].

At this point, it is deemed appropriate to state again the efficiency of a modern hydrogen fuel cell (80%), but it was not considered as an option for reasons described earlier.

Based on all these facts, a table summing up all the preceding efficiencies is given below. Note that direct electricity as an energy carrier is excluded because it does not involve any thermodynamic processes (not referring to the generation method) and practically, as it is the best possible scenario, it can be assumed to be 100% efficient.

<table>
<thead>
<tr>
<th>Drivetrain/Powertrain</th>
<th>Brake Thermal/Conversion Efficiency</th>
<th>Electricity Generator Efficiency</th>
<th>Management/Control (including backup battery energy when required)</th>
<th>Drivetrain/Powertrain Efficiency (including transmission losses)</th>
<th>Total Efficiency (Wheel Efficiency)</th>
<th>Improvement Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Engine Direct Drive</td>
<td>40%</td>
<td>N/A</td>
<td>N/A</td>
<td>63%</td>
<td>25.3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Diesel Engine Hybrid Electric in Series</td>
<td>40%</td>
<td>95%</td>
<td>95%</td>
<td>95%</td>
<td>34.3%</td>
<td>1.4</td>
</tr>
<tr>
<td>Gas turbine/Stirling Engine Hybrid Electric in Series</td>
<td>50%</td>
<td>95%</td>
<td>95%</td>
<td>95%</td>
<td>42.0%</td>
<td>1.7</td>
</tr>
<tr>
<td>Diesel Engine/Stirling Engine Hybrid Electric in Series</td>
<td>70%</td>
<td>95%</td>
<td>95%</td>
<td>95%</td>
<td>88.0%</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 1 – Total Efficiencies of various Powertrains/Drivetrains.

Clearly, Diesel Engine/Stirling Engine Hybrid Electric in series scenario is the superlative choice as it can be 2.4 times more efficient compared to conventional diesel engines with direct drives. Furthermore, this directly implies that fuel consumption and, thus, fuel costs can be reduced by a 2.4 factor as well, irrespective of chosen combustible fuel. The next best arrangement of a combined Brayton (gas turbine) with a Stirling engine scenario into a Hybrid Electric arrangement is promising as well, with an improvement factor of 1.7. Both of these arrangements could potentially be pertinent solutions until the large scale realization of E-highways, or even prevail as the only solutions for long-range heavy-duty freight trucks fuelled in the future solely on renewable biofuels.
All the presented technologies could operate with the current fossil fuels. Perhaps this is an alluring practice for the present as well, as significant savings in greenhouse gas emissions could be achieved. Most certainly, case studies must be evaluated, and trial tests should commence as the current work stands only as a proof of concept via a theoretical mostly investigation. It is believed, though, that since these are relatively mature technologies, their prompt advancement and application should not be a problem.

Lastly, the cost of implementing any of the proposed solutions should not be that extravagant, as the main extra cost (compared to conventional vehicles) of any electric vehicle is, actually, the battery and, to a much lesser degree, the electric motors and power electronics [88]. Considering that without a direct drive, the transmission and differentials are no longer required, the final manufacturing cost of such freight trucks, including the considerably smaller battery and the cost of electric motors, should be around the same or slightly higher compared to conventional trucks. It is rather arduous to assess at this point the exact final price. However, it is estimated that even if the total cost is moderately elevated, the significantly reduced running costs should compensate for that within the first few months of ownership, considering the distances these types of vehicles drive on a daily basis.
6. CONCLUDING DISCUSSION

Although the automotive manufacturers have invested a great deal of money and time in battery electric vehicles (BEVs), it is uncertain whether electricity as fuel will prevail in the end. That is especially the case for heavy-duty, long-range freight trucks. Furthermore, there are specific problems with a possible full-scale introduction of electric vehicles in the market as the current power generation capability and power grid infrastructures are certainly not able to support such an act. Even with the replacement of traditional fossil fuel power plants with numerous (to meet demand) renewable and/or nuclear ones, major upgrades in electric power infrastructure must be achieved after the depletion of the available fossil fuels. This can have a tremendous economic impact, even if it occurs gradually, especially in weaker/poorer economies. Furthermore, to achieve a sustainable, controllable charging strategy, radical social and behavioral changes must be realized, where the users will charge their vehicles not when they want but rather when it is reasonable and viable. Last but not least, for almost 100 years, petroleum and shipping companies have established an immense distribution network for fuelling, employing millions of people. With a 100% market penetration of BEVs, even if we overcome all the arising obstacles, their business operations would be rendered obsolete on all scales, especially on the distribution level.

Nevertheless, the world seems to progress gently forward with full electrification due to various mandates set by governments and agencies towards zero emissions, especially in urban areas. Hydrogen is another eco-friendly with zero emissions alternative, but the many hindrances in its handling, distribution, and storage seems to prevent its wide adoption.

Following the trends, freight trucks manufacturers are attempting to electrify their heavy-duty vehicles as well. However, there are major limitations to such an approach. Most importantly, the reduced mileage, long charging time, and the high cost of batteries for such energy-demanding applications are effectively limiting the operational, from a business perspective, capabilities of these vehicles. The most prominent suggested solution is the use of auxiliary power with overhead cables or underground conductive coils that could power and/or charge an electric freight truck as it drives through the highway. Indeed trials are showing promising results. The advantages are the high efficiency, flexibility, and more affordable cost for the vehicle, as a limited (smaller) battery capacity is required for energy storage. The reduced infrastructure cost of such installations compared with numerous massive charging stations along the highways should not be overlooked as well. Until an international adoption of such technology becomes a realization, international freight transit is not possible nonetheless. Moreover, this can be a limitation as well within the borders of individual countries, if not all of their highway network is equipped with the required infrastructure.

There is no doubt that electricity is the most efficient energy carrier of them all. However, until all obstacles are conquered, a very promising transition technology could be the coupling of a Diesel engine with a Stirling engine in a Hybrid Electric in-series arrangement. Reduced fuel consumption and hence emissions by a factor of 2.4 (60% wheel efficiency) compared to a standard direct-drive Diesel engine truck (25.2% wheel efficiency) are
theoretically possible. The cost of such a truck is estimated to be similar or slightly elevated compared to their conventional equivalents, but this could be compensated by the reduced running costs swiftly. The next best option is the coupling of a gas turbine with a Stirling engine in a Hybrid Electric in-series arrangement (42.9% wheel efficiency, improvement factor: 1.7) and lastly a standalone Diesel engine in a Hybrid Electric in-series arrangement (34.3% wheel efficiency, improvement factor: 1.4). All these approaches could work well with currently available fossil fuels (natural gas, diesel, etc.) as well as biofuels and overhead cables.

Expanding on that, the third generation of biofuels can probably provide a sustainable, eco-friendly, and inexpensive alternative fuelling solution for heavy-duty vehicles in the future, if employed with the aforementioned technology. Thus, some of the burdens of future electricity need supporting individual mobility, and required infrastructure changes (on the grid) can be alleviated. Lastly, the current fuel distribution networks and hence distribution companies could be operated as usual (business-as-usual), and perhaps the electrification of mobility could proceed only in congested urban areas.
7. FUTURE STUDIES

This work conferred some theoretical concepts towards the future sustainability of the next generation of freight trucks. The suggested powertrains/drivetrains were discussed from a theoretical point of view as a proof of concept. In this brief section, the appropriate next steps for the continuation of this study will be laid down.

Firstly, before the actual study (scale and design) of any potential solution described in this thesis, a bounding framework must be established. That is, the specific power requirements of an actual long-range freight truck, that will define the exact power output of the combined power plant.

Things that need to be considered:

- a) Weight (fully loaded), and hence rolling resistance (including friction) at 6% - 10% slope (i.e., driving uphill or climbing a mountain).
- b) Typical highway max. allowed speed (90 Km/h) and respective air drag coefficient/resistance.
- c) Efficiencies of Electric Motors and Power Electronics (i.e., as they were shown in Table 1).

Based on the latter, a combined power plant’s nominal capacity (‘sweet spot’) can be deduced, accounting a 10% - 15% extra margin for errors (higher design power output). This evaluated output will stand for the maximum power that the freight truck will require at all times. At maximum output, there will be no extra power for battery charging. However, the battery should be able to charge at times when the freight truck is driving under normal conditions on the highway (0% slope, 90 Km/h). The battery pack should be able to provide electricity for at least 50 Km (standalone) under normal driving conditions, approximately.

Based on all these facts, thermodynamic calculations can commence. The final step is the actual design of such a system followed by trials, which can be another new study by itself.
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