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Electricity as an Energy Carrier in Transport

- Cost and Efficiency Comparison of Different Pathways -

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ABSTRACT: This study includes a techno-economic assessment of different pathways of using electricity in passenger cars and short sea ships, with a special focus on electrofuels (i.e.fuels produced from electricity, water and CO_2) and electric road systems (ERS). For passenger cars electro-diesel is shown to be cost-competitive compare to battery electric vehicles with larger batteries (BEV50kWh) and hydrogen fuel cell vehicles (FCEV), assuming optimistic cost for the electrolyser. ERS is shown to reduce the vehicle cost substantially compare to BEV50kWh and FCEV, but depend on a new large scale infrastructure. For ships it is shown that battery electric vessels with a relatively small battery has the lowest cost. Electro-diesel and hydrogen can compete with the battery options only when ships operate few days per year.

KEY WORDS: cost comparison, electrofuels, electric vehicles, hydrogen, ships

1. INTRODUCTION

Electricity can be used in different forms in transportation as a way to improve energy efficiency and reduce environmental and climate impacts from the sector. It can be used (1) directly in electric engines, stored in batteries or using dynamic power transfer while driving (electric road systems; ERS, i.e., dynamic power transfer while driving); (2) to produce hydrogen and run in fuel cells or (3) to produce electrofuels, also known as power-to-liquid or synthetic fuels, from carbon dioxide (CO_2) water, and electricity and run in internal combustion engines.

It is not obvious which of these pathways that are optimal for the transport sector when moving away from fossil fuels, since each alternatives has its own advantages and disadvantages, where cost aspects is of special interest. All the different pathways of using electricity in the transport sector are illustrated in Fig. 1. In Table 1, the efficiency values from electricity sources to wheels, the main advantages and challenges are presented for the electricity pathways seen in Fig. 1.

Present electric vehicles using static charging have a high efficiency from electricity sources to the wheels (~73%)(1), but suffer from short driving range compared to conventional vehicles or fuel cell vehicles. Electrofuels and hydrogen face supply-chain efficiency issues with losses of more than 88% in several energy conversion steps before end-use(2).

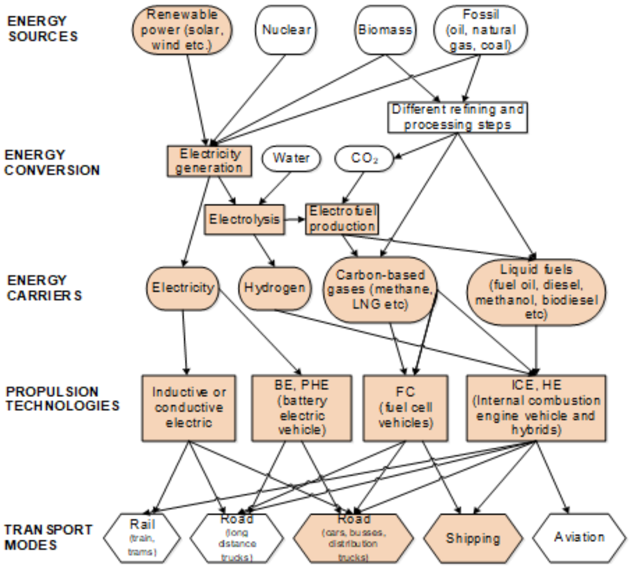

Fig. 1 Simplified schematic of primary energy sources, energy conversion technologies, and energy carriers for different transport modes. The coloured boxes are assessed in this paper. LNG=liquefied natural gas, ICE=internal combustion engines, HE=hybrid electric propulsion, FC=fuel cells, BE=battery electric propulsion, PHE=plug-in hybrid electric propulsion.

However, electrofuels can be used in combustion engines and may not require significant investments in new infrastructure (that often has very high up-front costs). In a calculation example of the

Scandinavian countries, a full electrification of road transport using hydrogen or electrofuels would increase the electricity demand with more than 100%, while direct use of electricity through static charging or ERS would increase the electricity demand with approximately 25%, as seen in Table 1. However, it is not obvious that indirect electrification of transportation (i.e. electrofuels or hydrogen) is less advantageous than direct electricity use, since hydrogen and/or electrofuels offer possibilities of energy storage, as well as, these fuels might be produced during periods of excess electricity generation and low electricity prices. Electric road system has a high efficiency from electricity sources to the wheels (~77%)(1) and can reduce the vehicle investment cost by reducing the on-board battery, but requires a new infrastructure with high upfront investment costs.

Table 1 Efficiency values from electricity sources to wheels, main advantages and challenges for different transport options.

Transport options	**Efficiency(1)**	**Increase of electricity demand (Scandinavia)**	**Main advantages**	**Main challenges**
EV (batteries)	73%	25%	✶ Quiet and zero tailpipe emissions ✶ High efficiency	× Short driving range compare to combustion engine vehicles × Heavy batteries for trucks and buses
Electric road systems (ERS)	77%	24%	✶ Quiet and zero tailpipe emissions ✶ Smaller on-board batteries than EVs with static charging ✶ High efficiency	×New infrastructure with high upfront investment costs ×Technical challenges with the inductive power transfer technology
Electro-fuels (E-diesel)	17%	140%	✶ Fast refuelling time ✶ All transport modes ✶ Can use current infrastructure and vehicles	× Low efficiency × Tailpipe emissions × captured CO_2 molecules are recycled (and released to atmosphere after combustion) instead of stored
Hydrogen	24%	110%	✶ Fast refuelling time ✶ Quiet and zero tailpipe emissions	× Low efficiency × New infrastructure with high upfront investment costs × Difficulties associated with storage

Several previous studies(4-8) have carried out similar techno-economic assessments or total cost of ownership of electrifying the road transport sector in order to compare the cost for different alternative pathways with each other. For example, Boer et al(4) compared the techno-economic cost of using different zero emission alternatives for trucks. Wolfram and Lutsey(8) compared the component cost for three electric propulsion systems (battery electric vehicles, plug-in hybrid electric vehicles, and hydrogen fuel cell electric vehicles) using current technology costs and cost projections for Year 2030. Their conclusion is that the power train costs for all three type are expected to decrease further, by 50%–70% between 2015 and 2030 if implementing policies. Very few studies analysing and comparing vehicle costs have included also the relative new options of ERS and electrofuels.

This study investigates the cost and efficiency of these electricity pathways for use in cars, trucks and ships using a techno-economic assessment. The techno-economic assessment takes into consideration (i) the production cost of electricity, (i) distribution cost of electricity, (iii) the production and distribution cost of hydrogen and electrofuels, and (iv) the cost of electric road and vehicle cost. The assessment is done for different ways of using electricity for transport, thereby excluding comparison with fossil and biofuels. All cost calculations are excluding taxes and subsidies. The different electricity pathways, illustrated in Fig. 1, have today different technology readiness level (i.e., are not at the same maturity state), which will have an impact on the cost competitiveness today. The focus in this study is on the future potential of the different pathways and therefore cost estimates for approximately year 2030 is used to compare the pathways when reach the same TRL level.

2. METHOD

2.1. Electrification pathways, vehicle and ship assumptions and calculation scenarios

In total seven different electrification pathways or combination of pathways are investigated for the passenger vehicles: (i-iii) battery electric vehicles, with a battery size of 15 kWh, 30 kWh and 50 kWh, assuming fast charging for the distance longer than the battery range (BEV-15kWh, BEV-30kWh and BEV-50kWh); (iv) battery electric vehicle with a battery size of 15 kWh assuming electric road systems covering the distance longer than the battery range (BEV-15kWh-ERS); (v) electrofuels using a diesel combustion engine (E-diesel); (vi) plug-in hydrid vehicle with 15 kWh battery using E-diesel for trips longer than the battery range

(PHEV-15kWh-Ediesel); and (vii) hydrogen fuel cell vehicles (FCEV). The distance covered by the battery is assumed to be 77%, 92% and 95% for the three battery sizes 15 kWh, 30 kWh and 50 kWh respectively, based on analysis of GPS measurements of about 770 randomly chosen gasoline and diesel vehicles that completed 107,910 trips between years 2010 and 2012 in west of Sweden(9). Five different electriciation pathways are analyzed for a short sea operating ship: (i) battery electric, with an operational capacity of 12h, 24h and 48h before charging (BE-12h, BE-24h, BE-48h); (ii) electrofuels using a diesel combustion engine (E-diesel); (iii) fuel cell vehicles using hydrogen as fuel (FCEV).

All cost calculations are made for two scenarios: (i) an optimistic scenario for electrofuels and hydrogen assuming optimistic cost projections for fuel cells and electrolysers; and (ii) an optimistic scenarios for using battery electric vehicles assuming optimistic cost projections for batteries, electric engine and electric road system infrastructure.

2.2. Cost and technology assumptions

Table 2 shows technology and vehicle specifications and costs for the base and optimistic case. The interest rate is set to 5% and a currency exchange of 0.89 USD per Euro has been used. The technical lifetime for passenger cars and ships is assumed to be 10 and 30 years respectively. The fuel consumption for the BEV, FCEV and E-diesel passenger cars are set to 0.18 kWh/km, $7gH_2$/km and 0.05 l/km, respectively.

The extra vehicle cost for a truck using an ERS (i.e., some kind of pick-up system) is estimated by Olsson(10) to be in the range of ~5000 €. A much lower cost for passenger cars and vans can be expected, since those vehicles will need a power transfer rate of ~50 kW instead of ~200 kW. A battery cost review has been done by Nyqvist and Nilsson(11) estimating the costs of Li-ion battery packs will continue to decline until year 2030, reaching costs in the range of 150 $/kWh. The cost of fuel cells is also uncertain, but estimated to decline in cost when being produced at larger scale. For example, Wolfram and Lutsey(8) estimates the fuel cel system production cost to be 21-32 €/kW in 2020 based on a literature review of a number of studies. The cost for the electric engine is estimated to be in the range 7-15 €/kW for year 2030 and beyond(12).

Table 2 Technology and vehicle specifications and costs. The value for ships is added in parenthesis when values are differentiated between passenger cars and ships.

	Optimistic	Base	Efficiency	Passenger cars	Ships
Electric engine/ combustion engine	10/30 (40/400) [€/kW]	15/30 (80/400) [€/kW]	90%/40% (90%/45%)	80 [kW]/80[kW]*	2400 [kW]/ 2400[kW]
Battery	100 (150) [€/kWh]	150 (300) [€/kWh]	88% (roundtrip)	15, 30 and 50 [kWh]	30, 60, 120 [MWh]
Fuel cell	25 (600) [€/kW]	30 (1200) [€/kW]	65% (55%)	80 [kW]	2400 [kW]
Vehicle/vessel chassi and body	-	-	-	12,000 [€]	11.4 [M€]
Diesel tank	1.9 [€/kWh] (0.1 [€/kWh])	1.9 [€/kWh] (0.1 [€/kWh])	-	66 [kWh]	170 [MWh]
Hydrogen tank	575 [€/kg] (2 [€/kWh])	575 [€/kg] (2 [€/kWh])		5 [kg]	170 [MWh]
Electricity pick-up system (ERS)	-	-	95%	1000 [€/car]	-

**the PHEV has both an electric and combustion engine with sizes of 60 kW and 70 kW respectively.*

Table 3 shows infrastructure and fuel costs used in this study. The electricity production cost is set to 50 €/MWh in base case, corresponding to the current average electricity prices in Europe. An additional distribution infrastructure cost of 20 €/MWh is added to the electricity price. The cost for fast charging has been estimated by Gnann et al.(13) to be between 0.05–0.35 €/kWh, mainly depending on charging power capacity and acceptance of queing time. Their study uses current charging behavior from a large charging data set from Sweden and Norway and take the findings to calibrate a queuing model for future fast charging infrastructure needs and costs. The infrastructure cost for ERS (including the grid connection) has a broad cost range in the literature ranging from 0.4 M€/km to 5 M€/km of electrified road(10,14,15). Taljegard et al.(16) have further estimated the cost for ERS infrastructure per vehicle kilometer to be between 0.03-0.5 € per vehicle kilometre depending, of course, on the road traffic volumes. A majority of the main road network in Sweden will have a cost in between 0.03-0.07 €/km if ERS are being implemented and used at large scale(16). The fuel cost for hydrogen and E-diesel are taken from the base and optimistic case for 2030 in Brynolf et al.(2), who have done an extensive literature review of the production costs of these fuels. Cost for hydrogen liqufication, and distribution of E-diesel and hydrogen, have been added to the fuel production costs as seen in Table 3.

Table 3 Infrastructure and fuel costs. The value for ships is added in parenthesis when values are differentiated between passenger cars and ships.

	Production cost (Optimistic/base)	**Infrastructure (Optimistic/base)**	**Passenger car driving cost (Optimistic/base)**	**Ships running cost (Optimistic/base)**
Electricity	50 [€/MWh]	20 [€/MWh]	0.012 [€/km]	3200 [€/day]
E-diesel	1.24/1.90 [€/l] (112/180 [€/MWh])	0.15 [€/l] (0.02 €/kWh)	0.062 [€/km]	20,700 [€/day]
Hydrogen	2.8/3.9 [€/kg] (84/116 [€/MWh])	2 [€/kg] (0.04 €/kWh)	0.03/0.04 [€/km]	12,100 [€/day]
Electric road system using electricity	50 [€/MWh]	0.05/0.07 [€/km]	0.06/0.08 [€/km]	-
Fast charging using electricity	50 [€/MWh]	0.06 [€/km]	0.07 [€/km]	-

3. RESULTS

Results indicates that there is a trade-off between the cost and efficiency to produce the energy carrier (direct electricity as well as indirect electricity in the form of hydrogen or electrofuels) and the cost of the propulsion and energy storage technologies (batteries, electric roads, fuel cells, hydrogen storage and internal combustion engines).

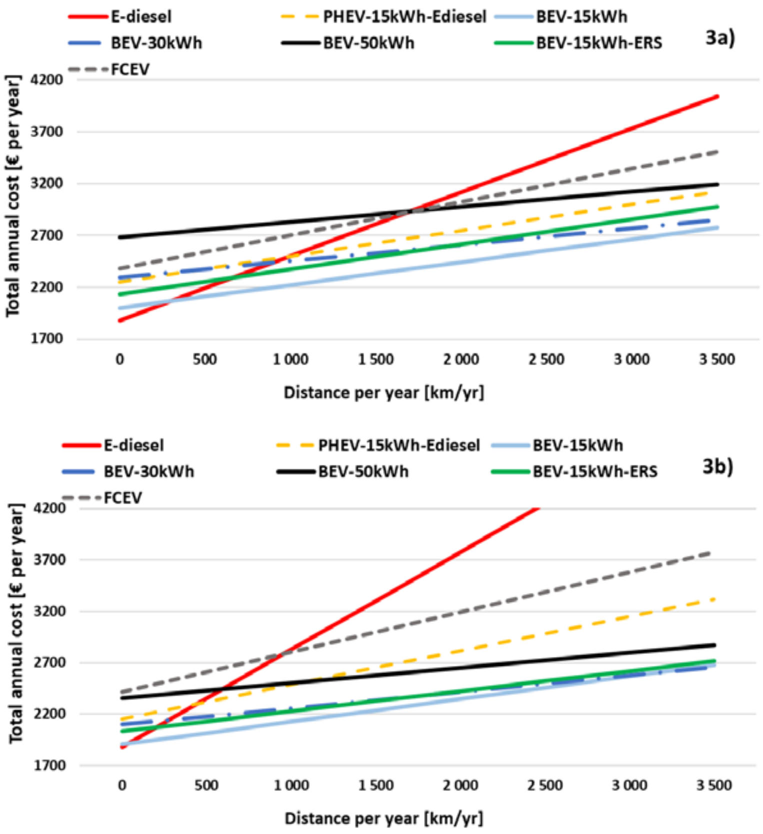

Fig 2. The total cost per year as a function of the yearly driving distance for different ways of using electricity for passenger cars in (a) an optimistic scenario for electrofuels and hydrogen, and (b) an optimistic scenarios for using battery electric vehicles. Abbrevations used: BEV=battery electric vehicle; FCEV=hydrogen fuel cell vehicle; PHEV=plug-in hydrid vehicle using electricity and e-diesel; E-diesel=synthetic diesel (electro-diesel); ERS=electric road system.

3.1. Passenger cars

Results for the cost comparison between the seven different options of using electricity as energy carier, are presented in Fig. 2. and shows the total cost per year as a function of the yearly driving distance for an optimistic scenario regarding future cost of electrofuels and hydrogen (Fig 2a) and an optimistic scenario regading future cost of battery electric vehicles (Fig 2b).

There are several interesting results. First, the most cost competitive solution in both Fig 2a and Fig. 2b, and for almost all annually driving distances, is to use a BEV with a relatively small battery and then stop and fast charge for the longer trips outside the battery range. Currently, there seems to be a willingness to pay for avoiding range anxiety, since new models of EVs have larger and larger batteries, even though the full battery range is used for very few of the trips (often less than 5% of the trips(9)). The larger BEV with a battery size of 50 kWh is shown as the most (Fig 2a) and the second most (Fig 2b) costly solution for short annual use.

Second, ERS might also be an attractive option, where the small batteries reduces the cost of each individual vehicle but adds a cost for a common infrastructure shared by many vehicles over a long time period. Even when increasing the cost of ERS (Fig 2a), this seems to be a cost competitive solution. One issue with ERS for passenger cars is that each individual car are conducting trips on all main road network (i.e., not driving in a shuttle-service), which would require a large ERS network to be built before being able to reduce the size of the on-board battery. Additionally, infrastructure takes time to build and has high upfront investment costs that needs an attractive business model in order for it to be built.

Third, in the optimistic cost scenario for E-diesel (Fig. 2a), E-diesel are cost-competitive with BEV-50 kWh for the yearly driving range of up to 16,000 km per year. The lower investment costs for the E-diesel, compare to BEV-50 kWh, makes E-diesel competitive for short driving ranges. However, at longer driving ranges the fuel cost, of the total cost, becomes more dominant and E-diesel is, of course, much more costly per kilometer than electricity. A PHEV with a 15 kWh battery using E-diesel as range extender, is relatively cost-competitive compared to BEV-50kWh and FCEV, however only for the case with optimistic E-diesel costs (Fig. 2a). In the optimistic case for BEV, the high fuel cost for E-diesel becomes an issue for also the PHEV. In order to find E-diesel vehicles cost-competitive it seems important to bring down the production cost of E-diesel, where electrolysers are contributing the most to the high production cost of electrofuels(2).

Further, worth noticing in Fig. 2 is also that even in the optimistic case for hydrogen vehicles (Fig. 2a), both the relatively high production cost and vehicle cost, makes it difficult for the FCEV to compete with the other options. The industry, for example ion and steel industry in Sweden, is now investing in hydrogen projects to reduce the CO_2 emissions, by replacing the use of coal with hydrogen. If the use of hydrogen become large scale in several industries that might help to bring down production cost of hydrogen and develop an infrastructure for hydrogen also for the transport sector.

Fig. 3 shows the total cost per year for one yearly driving distance (15,000 km per year) but divided upon vehicle cost, fuel production cost and infrastructure cost. As seen in Fig 3, reducing the fuel cost for E-diesel is important to make electrofuels cost-competitive with the other options, where E-diesel in the optimitic case have a lower total annual cost than BEV-50kWh and FCEV. In Fig 3, one can also see that it is the lower cost for battery in the case with ERS, and the relatively low extra cost for using an ERS, making this solution cost-competitive.

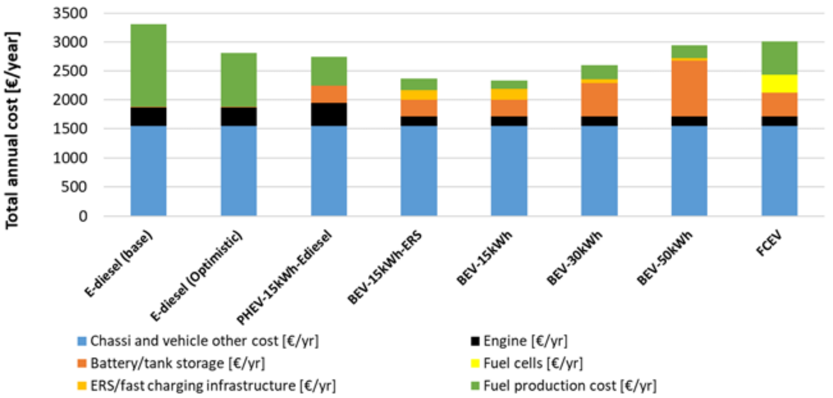

Fig. 3. The total cost per year divided upon vehicle cost, fuel production cost and infrastructure cost for the different ways of using electricity for passenger cars assuming an annual driving range of 15,000 km and the base case cost estimates.

3.2. Ships

Annual cost for the five ship categories is calculated depending on how many days they are operated per year, and results are presented in Fig 4.

Results show that the most cost competitive solution in both Figs 4a and 4b, almost regardless of how many days the ships are operated per year, is to use battery electric vessels with a relatively small battery (BE-12h). In both scenarios, the largest battery electric vessel (BE-48h) is shown to be the most costly option for ships operating few days per year, i.e up to approximately 240 and 60 days per year in Fig 4a and 4b respectively. Results on E-diesel show that in the optimistic scenario for electrofuels and hydrogen, the E-diesel option can compete with the two battery options BE-24h and BE-48h for ships operating few days per year, i.e up to approximately 120 and 240 days per year, respectively (Fig 4a). In the scenario assuming optimistic data on battery electric propulsion, all three battery operating vessels show lower total cost, compared to hydrogen and E-diesel when operating more than approximately 100 days per year (Fig 4b).

Comparing the costs for hydrogen FC option to the E-diesel option it is clear that they both increase, but deviate, with increased number of days the ship is operated, since the fuel cost of Electro-diesel is higher than the cost of hydrogen. The higher investment cost of fuel cell vessels is making the E-diesel option competitive (compared to hydrogen) only if the ship is operated less than approximately 50 days per year.

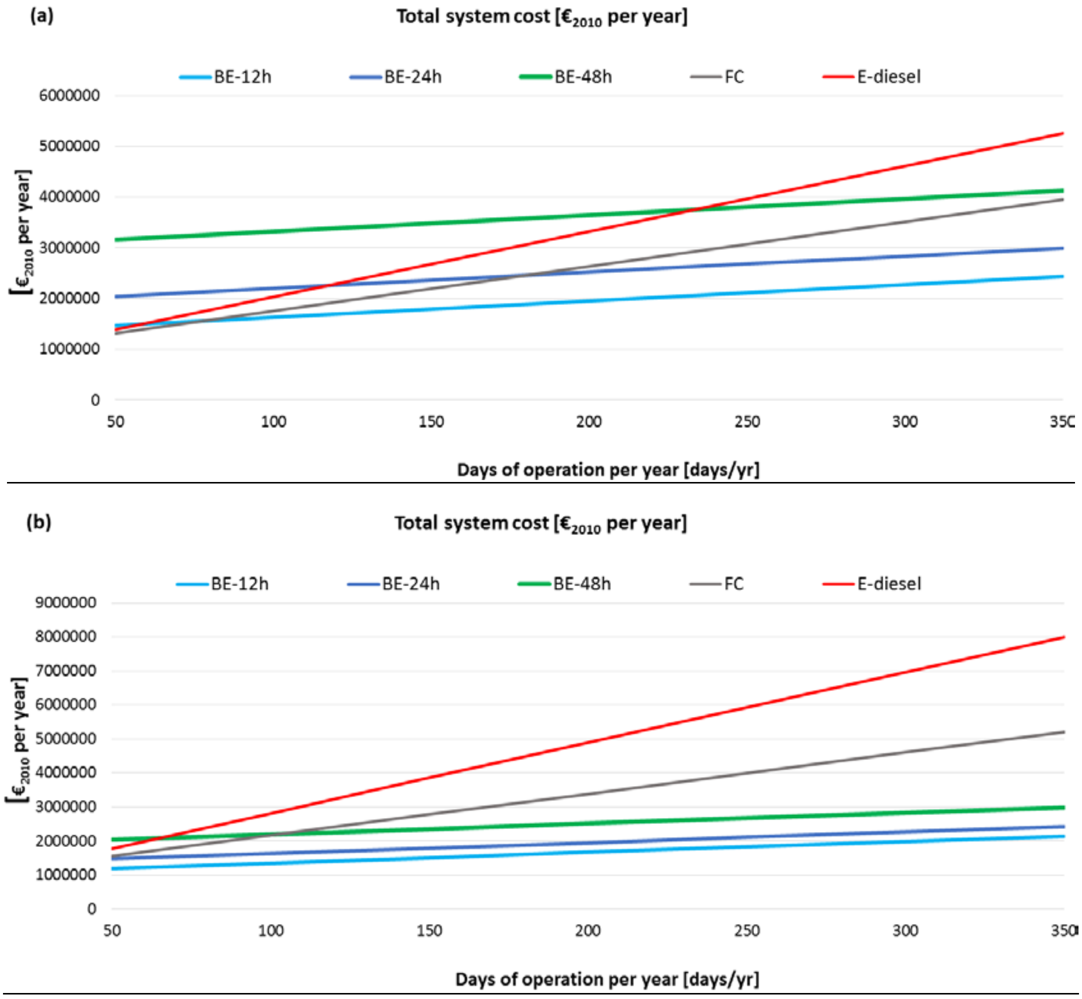

Fig.4. Cost-comparison of some potential pathways from electricity to transport service for a short sea ship depending on how many days they are operated per year in (a) an optimistic scenario for electrofuels and hydrogen, and (b) an optimistic scenarios for using battery electric propulsion . Abbreviations: E-diesel= synthetic diesel (electro-diesel), FC=Hydrogen fuel cell, BE=battery electric operation. The figures are based on data in Table 2 and Table 3.

3. DISCUSSION AND CONCLUSION

We have carried out a techno-economic assessment of different pathways of using electricity in passenger cars and short sea ships, with a special focus on electrofuels (i.e.fuels produced from electricity, water and CO_2) and electric road systems (ERS).

Results indicate that ERS have the potential to substantially reduce the vehicle costs, compare to BEV50kWh and FCEV, but depend on a new large scale infrastructure. For ships it is shown that battery electric vessels with a relatively small battery has the lowest cost. E-diesel and hydrogen can compete with the battery options only when ships operate few days per year. E-diesel can be competitive when vehicles and vessels operate only part time of the year, whereas battery vehicles and vessels have advantages when they are used for longer distances or more days over the year. It must be noted however that not all short sea ships can have such small operationg range as 12, 24 and 48h. For trips takning several days or when emergency backup is needed battery electic solution will have much more difficlut to compete with electrofuels and hydrogen.

That E-diesel is competivite for ships only used part time of the year can be understood from that if costs from relatively expensive investments, such as batteries or fuel cells, can be spread out over a large amount of operating hours (or km), the cost is less dominated by the investment, but more of the cost of fuel. When it is the fuel cost that dominates the total cost, hydrogen and direct electricity have advantages compared to the more expensive E-diesel fuel.

All cost assumptions made in this study are chosen to reflect mature technology around 2030 or beyond, and are of course associated with uncertainties. It should, however, be noted that the production cost of hydrogen always will be lower than the production cost of electrofuels since hydrogen is used as feedstock for the production of electrofuels. Further sensitivity analyses, e.g. using Monte Carlo simulations for testing combinations of uncertain data would improve the analysis. This is planned as the next step for this study.

Important to note is that if electrofuels are used as drop-in fuels, although they may offer a solution for a fast transition away from fossil fuels, there is a risk that they may contribute to a prolonged era of fossil fuels. Regarding effects on human health, such as the local emissions NOx and soot, from combustion engines would also remain in the case where electrofuels are used in conventional internal combustion engines The majority of these local emissions can, on the other hand, be reduced with exhaust after treatment technologies. For traffic outside cities, local emissions are of less concern for human health, simplifying the use of electrofuels in ships, and long-distance road transport.

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