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Wise use of renewable energy in transport

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ABSTRACT

The transport sector accounts for around 25 % of global energy use, considering both fuel production and consumption. To mitigate climate change, a fast decarbonization of transport is therefore often seen as a necessity, as advocated by the International Energy Agency in its *Net Zero by 2050* scenario. In contrast, Shell's *Sky* scenario envisages Net Zero by 2070 by first picking the lowest hanging fruits within all sectors, and hence a much slower de-carbonization of the transport sector. We investigate how renewables, a scarce resource over the next decades, could be used most wisely within the transport sector or alternatively within the energy sector. Our results stress that priority up to 2050 should be: First, to use new renewable energy to replace coal fired electricity production to nearly decarbonize the electricity grid; Second, to gradually electrify road transport; Third, continued use of fossil fuel in shipping and aviation.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) stresses the urgent need for rapid reduction of greenhouse gas (GHG) emissions to keep global temperature rise well below 2∘C compared to pre-industrial levels (IPCC, 2021; IPCC, 2022). Presently, 64 % of Global anthropogenic GHG emissions (IPCC, 2021) come in the form of CO_2 from burning fossil fuels for electricity generation, heat, power, and in industrial processes.

In 2020, global primary energy use was 611 Exajoule (EJ), and around 80 % came from fossil fuel (Shell, 2021). For conventional fossil fuels used in the transport sector, 20 % of their Well-to-Wheel/Wake (WTW) emissions come from fuel production and delivery, and 80 % from their direct use (Edwards et al., 2014; Prussi et al., 2020). According to Shell (2021), the transport sector's direct energy use measured Tank-to-Wheel/Wake (TTW) in 2020 added up to 119EJ, while for their production measured Well-to-Tank (WTT) there is no direct sector-wise reporting. Nevertheless, for fossil fuels, which covers more than 95 % of the transport sector's energy use, there is nearly a one-to-one relationship between CO_2 emissions and energy use. The WTW energy use of the transport sector can hence be estimated by combining its 119EJ used TTW, with its WTT energy use of (119EJ/0.8) * 0.2 = 30EJ, yielding 149 EJ, representing around 25 % of the global primary energy use.

With a quarter of GHG emissions, a fast de-carbonization of the transport sector is therefore generally seen as a necessity, as advocated in the *Net Zero by 2050 scenario* by the International Energy Agency (IEA), published in May 2021 (IEA, 2021). IEA's Net

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Zero scenario relies on all sectors, also transport, doing their outmost to be fully decarbonized by 2050. In contrast, Shell's *Sky scenario* Shell (2021) envisages Net Zero in 2070 by first picking the lowest hanging fruits within all sectors.[1] As other sectors are seen as easier to de-carbonise than transport, *Shell Sky* in 2050 relies on nearly 100 % fossil fuel in maritime shipping and aviation, and about 70 % in road transport and 40 % in rail. To reach Net Zero GHG emissions, both IEA's and Shell's scenarios imply that all remaining anthropogenic GHG emissions are removed at the point of combustion or directly from the atmosphere (DAC). Compared to the 1202 scenarios in the AR6 WG III database (IPCC 2022a), which passed all vetting criteria (Kikstra et al., 2022), the Net Zero by IEA is one of a few which gives a pathway to limit global warming to 1.5 °C, with more than 50 % certainty (NGFS, 2022). The Shell Sky scenario envisages a peak of 1.7 – 1.8 °C in 2070 followed by a drop to 1.5 °C before 2100, and therefore in our judgment belongs to the *C*2. The C1 and the *C*2 group are followed by C3 and C4 with scenarios which limits warming to 2 °C. Other scenarios with greater climate change are grouped in the categories C5, C6, C7 that limits warming to 2.5 °C, 3 °C, and 4 °C, in C8 we find the scenarios that exceed warming with more than 4 °C (Schleussner et al., 2022).

Our research can be related to transportation system modelling that describes how future demand for transport can be fulfilled through different modes of technologies under different climate change mitigation targets or policies (IPCC AR6 WGIII, Annex 3). In these models, GHG emissions from transport are largely a function of travel demand, transport mode, and transport technology/fuel. In our context, the question is on what could be a wise use of renewable energy based on key assumptions on the adoption of advanced fuels and for given *what-if* scenarios derived from "IAE and Shell". Basically, there are three approaches to model transportation systems: by optimization, by simulation and by accounting and exploratory. Our method is an accounting and exploratory approach that considers that the key decision variables such as new technologies adoptions typically follow modeler's assumptions as opposed to being determined by mathematical formulations. Our analysis is mostly based on energy use, conversion losses, and emissions. We consider important areas of future research to include economic evaluations that also incorporates prices, costs of capital, technology, and transition. While such analysis will be useful, it will itself include a range of additional issues, and build on assessments in terms of energy and emissions.

Transport can be decarbonized by switching from fossil fuels to zero-carbon E-fuels in the form of liquid or gaseous fuels made from renewable energy, by using the renewable electricity directly or in combination with batteries, or through biofuels. Compared to conventional fossil fuels and biofuels, the option of emission-free electricity in combination with batteries reduces the WTW energy consumption in transport. Contrary liquid or gaseous E-fuels, raises the WTW energy consumption in transport compared to fossil fuels (Lindstad et al., 2021; Brynolf et al., 2022). Both these options require a global ramp up of renewable electricity generation, less so for direct use of electricity, due to the energy costs of conversions to E-fuels. For biofuels, the ones made from garbage or waste might have zero- or even negative WTW emissions and a low energy use in their Well-to-Tank processing stages, but their availability is limited. In a worse case, biofuels may raise WTW emissions due to farmland use and even deforestation compared to their fossil counterparts (SSI, 2019, Lindstad et al 2021a).

Importantly, a major global ramp-up of renewable electricity generation, is a challenge both in terms of resources (capital, inter alia) and time. The current share of hydropower, sun and wind generation in the global energy mix global energy mix is only around 5 % (Shell, 2021). Considering the cited scenarios for future energy consumption and mix, Fig. 1 displays our estimates for the necessary corresponding expansion of annual renewable electricity generation up to 2050. The left panel displays global primary energy production (in EJ) and mix in 1990 and 2020 and four 2050-scenarios: (1) a 2050 Business-as-usual scenario (BAU) based on the 2020 energy mix and same continuous growth in energy demand as seen from 1990 to 2020; (2) the Shell Sky scenario; (3) the IEA Net Zero scenario; (4) a BAU energy demand growth scenario combined with no GHG emissions, i.e. if all fossil energy would be replaced by renewable electricity. The right side of Fig. 1 displays the required annual increase in renewable electricity generation from 2020 to 2050 for each of the four scenarios, and the actual annual increase from 1990 to 2020 as a benchmark.

The main observations from Fig. 1 are: First, with a business-as-usual assumption, renewable electricity generation increases with around 2.5 EJ per year up to 2050; Second, under Net Zero scenarios, both IEA and Shell raise annual renewable electricity generation of 6 to 7 EJ up to 2050; Third, full decarbonization by 2050 under business-as-usual assumptions without Carbon Capture and Storage (CCS) would require an annual increase in renewable electricity generation up to 30EJ. This based on the assumption that conversion losses from primary energy to final usage will not change when the energy system is decarbonised, which might be the case if liquid or gaseous E-fuels play a major role in transport sector and a significant share of other sectors' decarbonisation, since they raise WTW energy consumption compared to conventional fuels (Lindstad et al., 2021; Brynolf et al., 2022). On the other hand, if renewable electricity in combination with batteries becomes the dominant solution in transport and renewable electricity on its own in other sectors, the 30 EJ estimate becomes far too high.

In total this implies that in a world where all sectors will try to de-carbonize before 2050, a continuous shortage of renewable electricity is likely, and requires wise prioritization of renewable energy within the transport sector and between sectors.

This paper proceeds as follows: Section 2 contains a literature review of existing research on decarbonization in the transport sector, shedding light on the lack of cross-sectorial studies. Section 3 presents a method (model) l to question the equal use of renewable energy in all sectors versus our perspective along the Well-to-Wheel/Wake axis. The analysis and results are presented in section 4 and discussed in section 5.

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[1] Another difference between the two scenarios is that Shell assumes a 30% increase in global energy use up to 2050 while IEA foresees a 10% reduction compared to 2020.

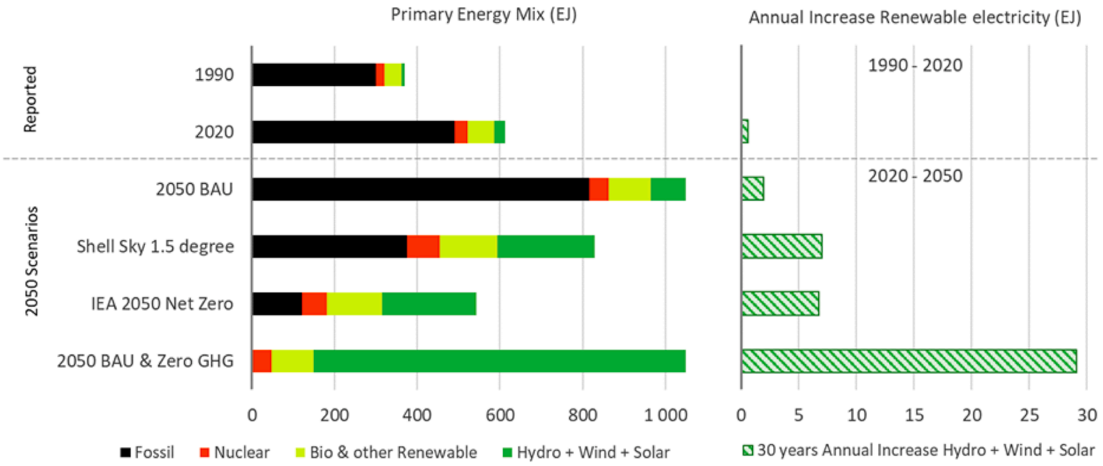

Fig. 1. Global Primary Energy Mix and required annual Increase in Renewable Electricity generation from 2020 to 2050: Past and Future Scenarios[1] (Source: authors). [1]The convention applied for estimating the amount of primary energy is the *direct equivalent method* (one unit of electricity generated from renewables is equivalent to one unit of primary energy production), assuming that, overall conversion losses from primary energy to final usage will remain unchanged when the energy system is decarbonised.

2. Literature review

The subjects of the environmental impacts of transport and transport decarbonization have become well-established on research and political agendas. To provide an overview of academic research and on the main methods used, we carried out a Scopus search with keywords related to transport sector, emissions and decarbonization, fuel impact assessments and alternative solutions. The period covered is 2000–2021, and publications are filtered by the word appearance in title, abstract or publication's keyword. The main results of the literature review are summarized in Fig. 2 which shows the annual number of publications for each category.

The main observations from Fig. 2 are that nearly 50 000 publications were published on the topic of CO_2 or GHG emissions from 2000 to 2021, with a rapid increase in numbers after 2010. The large majority of studies on transport decarbonization is on GHG reduction potential and costs compared to a baseline. In these studies, the economic aspect is reported as the main challenge to competitiveness of alternative solutions either in the form of low-carbon fuel solutions, or pure renewable energy- and electricity-based solutions (E-fuels, batteries, electrification). Recent examples are Li et al (2022), of road transport electrification and green hydrogen, Barke et al. (2022): on sustainable aviation fuels, and Brynolf et al. (2022): on electro-fuel feasibility. Though the big challenge of high costs for renewable-based options is clearly stated in such studies, the required renewable electricity is typically not viewed as a bottleneck. In fact, a general assumption in studies based on full deployment of renewable energies seems to be not only availability of renewable electricity, but also the feasibility of 100 %-renewable energy mix. The issue of constraints in renewable energy growth rate has generally been overseen, and attention has been put on its theoretical feasibility (Floyd et al. 2020).

The work of Moriarty and Honnery (2021) on the feasibility of 100 % renewable energy-based world assesses energy sources based on the "energy return on energy invested". It indicates such feasibility only with drastic reduction in energy consumption, and that renewable energy alone is not realistic in the short term. Still, some studies raise both the question of sectoral decarbonization, and limited availability of renewable energy, and thus the question of energy allocation when all sectors are chasing zero emissions. According to a review by Hansen et al. (2019), a holistic cross-sectorial approach, also known as smart energy system approach (Lund et al., 2017), will emphasize cross-sectoral synergies.

Few studies have considered the link between the power and transport sectors. Robinius et al. (2017) raise the need for considering the relationship between these two-sectors (sector coupling principle). Ortiz-Imedio et al. (2021) focus on how transport decarbonization impacts the power sector, while Khalili et al. (2019) display transition scenarios for global transport. Lebrouhi et al. (2021) conduct feasibility studies, challenge analyses of the full electrification of road transport, and call for more coordination between transport- and energy sectors. In line with former studies, Lindstad et al. (2021) assess of alternative fuels considering their GHG reduction potential, costs, and also energy use. They conclude that a narrow, maritime transport perspective displays weaknesses in accounting for implications on global energy supply. In principle Integrated Assessment Models, describing pathways of decarbonizations as applied in the IPCC AR6 Scenario Explorer should cover the link between the energy systems and the transport sector. However, until the last 5 or so years, the electricity demands of the transportation sector were insignificant in most scenarios. Furthermore, most of the scenarios in the published archives don't include e-fuels; instead, they tend to have a heavy reliance on biofuels.

Thus, our literature review indicates that insufficient attention is given to the impact of transport sectors' decarbonization measures on the energy production sector. Cross-sectoral studies are needed, and these should focus on how to best use renewable energy during the transition towards zero GHG emissions. We thus analyse how the transport sector and each of its sub-sectors can best use renewable electricity, as well as when that renewable electricity is better used elsewhere. Since Transport and Electricity generation uses more

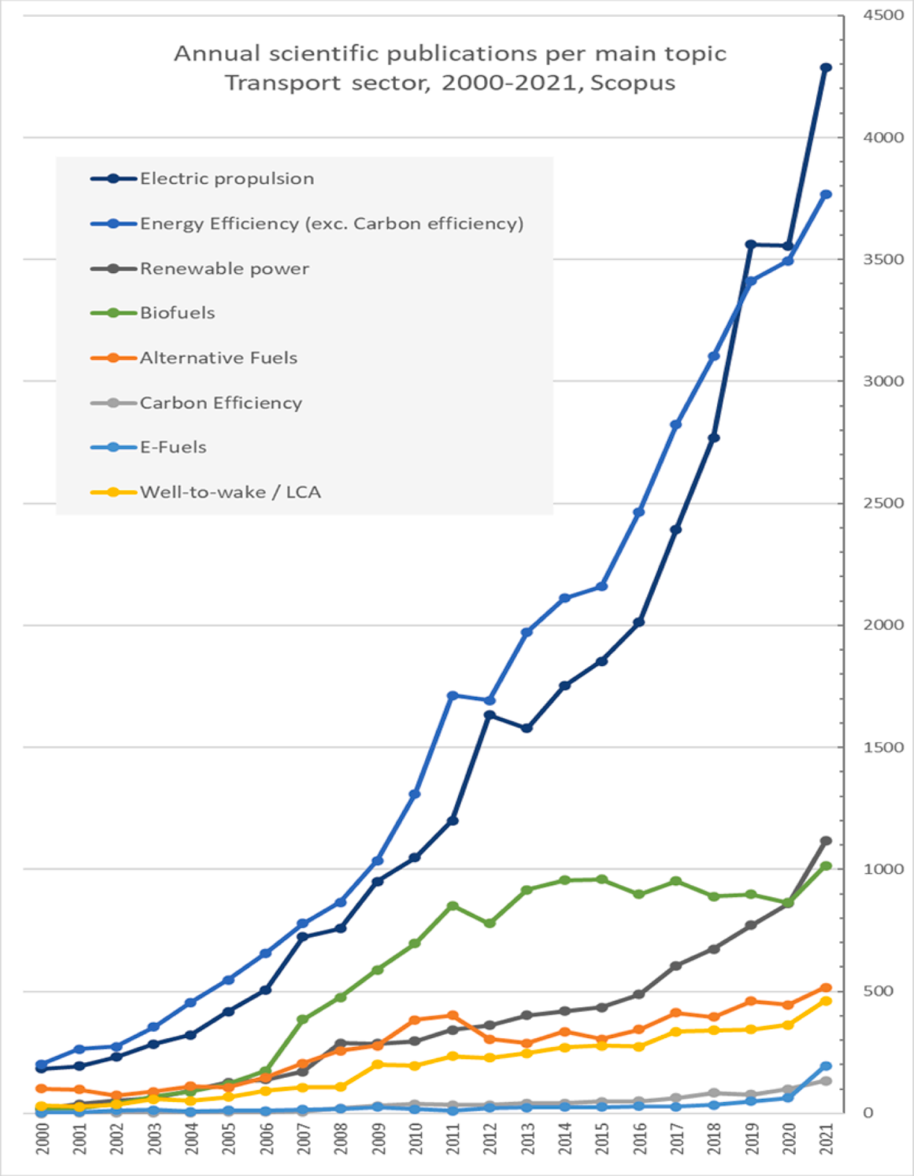

Fig. 2. Annual publications in Scopus database, by search category (Source: authors).

than 60 % of the world primary energy, “elsewhere” in this study means *in* electricity generation. The next section presents the framework applied in this research.

3. Method

To investigate how the transport sector best can use renewable electricity and when it is better used elsewhere, we identify feasible renewable-based options for each transport sectors. We then assess them in terms of the GHG reduction they offer, and we compare with alternative utilization of renewable electricity. The framework applied for assessment of these alternative renewable pathways is a Well-to-Wake based Life cycle Assessment (LCA) framework, following the LCA process defined by ISO 14040 LCA guidelines. This approach is in line with former work by Hwang et al (2019); Dong and Cai (2019) and Lindstad et al (2020) for assessing alternative fuel pathways. It consists in setting goal and scope of the study at hand, conducting an inventory analysis of the necessary data for the assessment, carrying out a WTW life-cycle impact assessment of the alternative energy pathways, and finally interpretating the results, by comparing alternative uses for renewable electricity.

The proposed WTW-based LCA methodology for the present study, as reported in Fig. 3, is articulated around two major impact factors: Climate Impact and Primary Energy usage. Climate impact is measured in WTW GHG emissions based on a one-hundred years-

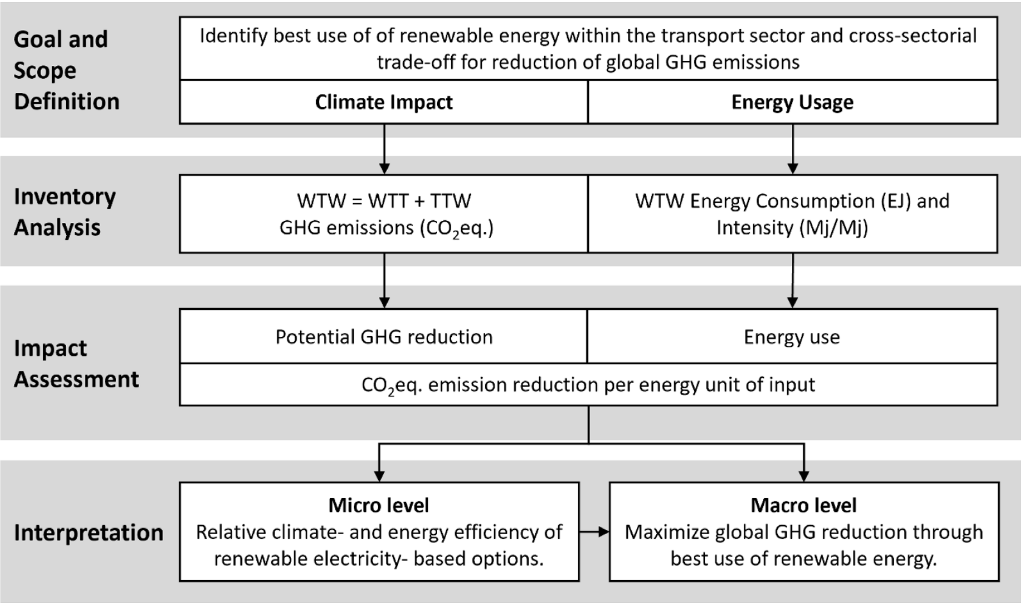

Fig. 3. The WTW LCA methodology applied to renewable-based options for transport sectors.

time horizon (GWP100), and Primary energy usage from fuel production (WTT) and combustion (TTW) is measured in unit of primary energy used for each unit of energy provided for propulsion.

4. Analysis

We perform the analysis stepwise with the four (4) steps as described in the methodology section. The Goal and Scope is formulated as: Identify best use of Renewable energy within the transport sector and cross-sectorial trade-off in terms of reduction of Global GHG emissions, i.e., when it is better used elsewhere to minimize Global GHG emissions. For the transport sector, the analysis is kept at transport mode level, with a separation between passenger and freight transport. Moreover, the term “elsewhere” does not as such set limitations to the study, but rather enables us to set limits based on the inventory analysis. Our assessment is based on GHG emissions and energy use, and energy use may also serve as a proxy for cost, as costs increase with higher energy use and decrease with lower use.

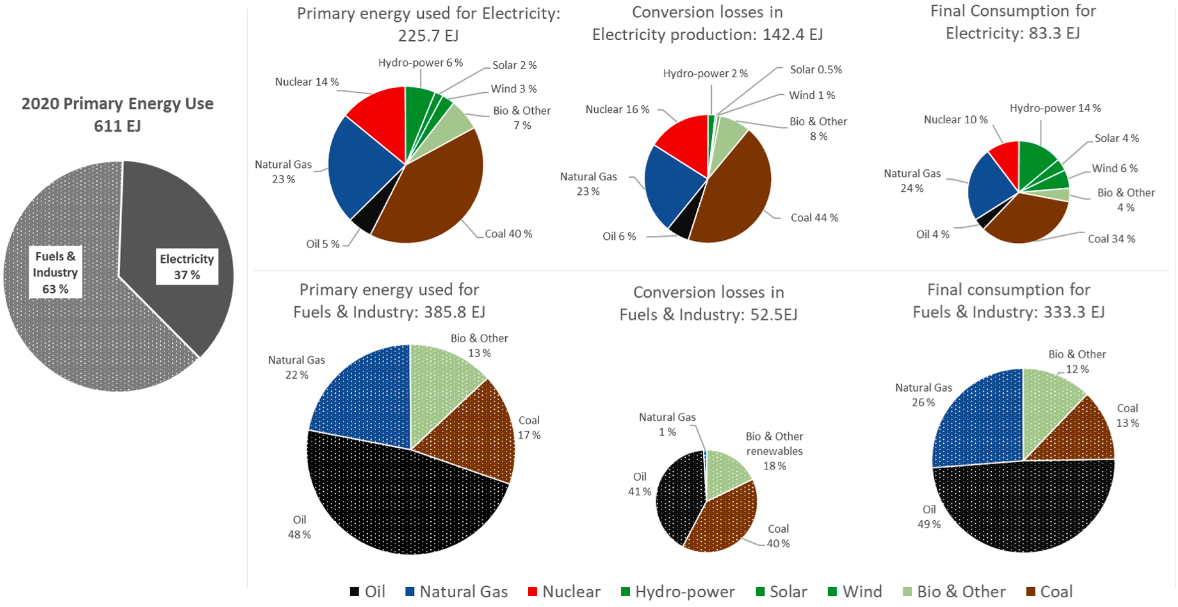

Fig. 4. Global energy use (source: compiled by authors based on Shell (2021)).

4.1. Global energy mix and electricity production

The starting point for the Inventory analysis is the Global energy mix, as shown in Fig. 4, based on 2020 energy figures published by Shell (2021). Compared to other energy statistics providers such as BP or IEA there are only marginal differences, and we choose to use the Shell dataset due to user-friendliness. Going from left to right in Fig. 4, the first pie shows a total energy (provision, or supply) use measured at the Well level (Primary energy use) of 611 EJ, of which 63 %, i.e., 385.8EJ are used for fuel production and industrial processes. The remaining 37 %, i.e., 225.7EJ are used to generate electricity. To the right are two rows, with the WTW chains for electricity at the top, and for fuel and industrial processes at the bottom. For both, the first pie shows the source of their primary energy use, and the second pie reports the conversion losses from Well-to-Tank. The third pie shows what remains for final consumption, after the conversion losses. It should be noted that the "conversion losses" identified in Fig. 4 in addition to the conversion losses in the energy transformation sectors (i.e., between primary energy and final energy), also include transmission and distribution losses in the electric grid. Basically, the cut-off point is the meter at each individual customer.

The main observations from Fig. 4 are as follows. First, 32 % of the total primary energy, 194 J out of 611 EJ, are lost in conversions and processing from Well-to-Tank; Second, the Well-to-Tank energy use for producing fuels and heat is less than half of this average, i.e., 14 %; Third, for electricity production, it is nearly twice the average level, i.e., 63 %.

With the current energy mix used for Global electricity generation (Shell, 2021), we can also estimate the amount of CO_2 emissions per kWh delivered to the grid. These values are given in Table 1,[2] displaying the amount of primary energy consumed, per energy source (column 1), the CO2 emission factors and amount from fossil energy (columns 2 and 3), the amount of electricity for final use after all conversion, transmission and distribution losses as displayed by column 4 (as measured at the meter of the customers), and the CO_2 emissions per kWh associated with final electricity consumption (column 5).

Estimates reported in Table 1 show first that the weighted average CO_2 emissions per kWh delivered to the electricity grid, all energy sources included, is 556 g per kWh. Natural gas has the lowest emissions of the fossil options with 552 g of CO_2 per kWh and coal the highest with 1131 g of CO_2 per kWh. Coal accounts for 70 % of the total CO_2 emissions but only contributes to 34 % of the final electricity supply. Replacing all coal in electricity generation with renewables would therefore reduce average CO_2 emissions from 556 to 168 g of CO_2 per kWh and most importantly reduce the annual Global anthropogenic CO_2 emissions with around 25 %, equivalent to nearly 9 out of the 35 billion ton of CO_2 (Shell, 2021).

4.2. Energy use WTW within the transport sector

Fig. 5 shows energy use WTW (per kilowatt hour propulsion) for alternative transport fuels, where green bars are used for the renewable options and grey for the fossil ones. It should be noted that the figures quoted in principle are unitless energy ratios, of primary energy inputs to final energy converted to propulsion.

Starting from the top with renewable electricity in combination with a type of battery used for electric cars, we need around 1.5kWh delivered from the windmill, sun-power, or the hydro power station to deliver 1 kWh propulsion at the wheels. This implies that 33 % of the energy is lost: through the grid, at the charging station, in the battery and through the electric motor and auxiliary units. Approximately half of this loss is lost through the grid and the other half is related to the battery and the electric motor. The 1.5kWh figure applies for any transport carrier, i.e., a truck, a bus, a ship, a train, or a plane using a battery to store its power. In contrast, if electricity is generated with the average global electricity mix rather than renewables only, we need 3.4kWh of Primary energy to deliver 1 on the wheels. This factor is estimated based on the following calculation: 225.7EJ/83.3EJ * $(1.5)^{1/2} = 3.4$ (as displayed by the second bar). The factor $(1.5)^{1/2}$, which approximately equals 1.225, corresponds to that half of the losses with electric cars and batteries and renewable electricity are related to the losses when the battery is charged, the battery losses and the losses in the electric motor, which are independent of the source of the electricity. While the other half of the losses is related the production and the distribution of the renewable electricity as can be read out of Table 1. In the case of coal-based electricity, the energy intensity is calculated as 91.11EJ /28.55EJ * $(1.5)^{1/2}$= 3.9 (bar 3 in Fig. 5). The rationale for here also displaying the performance with a purely coal fired electricity grid, is that with the current energy shortage in Europe from late 2021 onwards, the easiest way to replace shortcomings in natural gas deliveries has been to restart coal mines and coal powered electricity generation plants that were closed in previous years due to environmental reasons.

Bars 4, 5, 6 and 7 represent grey (fossil) fuels for transport. For sea transport with conventional fossil fuels (Diesel or Low sulphur bunker oil), we need 2.4kWh from the oil well to deliver 1kWh at the propeller with a typical average engine efficiency of 50 % (Lindstad et al., 2020). Road transport powered by diesel we need 3.1kWh of primary energy to deliver 1kWh on the wheels based on a typical average engine efficiency of 40 %. The calculation for this estimation is (1/0.8) * /0.40 = 3.1 where 1 is the combusted fuel and 0.8 is the Well-to-Tank part for producing the fuel (Edwards et al., 2014; Prussi et al., 2020). This 40 % average engine efficiency also applies to aircraft and since jet fuel is quite similar to diesel; the road WTW energy factor applies, i.e., 3.1. Finally, compared to all the options described above, a passenger car has the lowest average engine efficiency because it most of the time operates at a low power outtake with less efficient combustion, with a WTW energy use of 4.2 based on an average engine efficiency of 30 %, i.e., (1/0.8) * 1/0.30 = 4.2. Here the 30 % represents a mix of newer diesel and petrol cars with modern engines and not including older less efficient

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[2] In addition to CO_2, emissions of methane (CH_4) and some Nitrous oxide (N_2O) are also generated. However, due to shortcomings of the statistics we limit ourselves to CO_2 when assessing the GHG impact of electricity production.

Table 1
Primary energy mix and CO_2 emissions for Global electricity production.

	Primary energy (EJ)	CO_2 Emission Factors (ton CO_2 per TOE)	CO_2 Emitted (million ton)	Electricity for final use (EJ)	CO_2 emissions (Gram/kWh)
Hydro-power	14.20			11.61	
Solar	3.87			3.21	
Wind	5.96			4.84	
Bio & Other	14.88			3.52	
Nuclear	31.66			8.70	
Oil	11.57	3.20	884	3.23	985
Natural Gas	52.45	2.40	3 007	19.60	552
Coal	91.11	4.12	8 969	28.55	1 131
Total	225.70		12 860	83.26	556

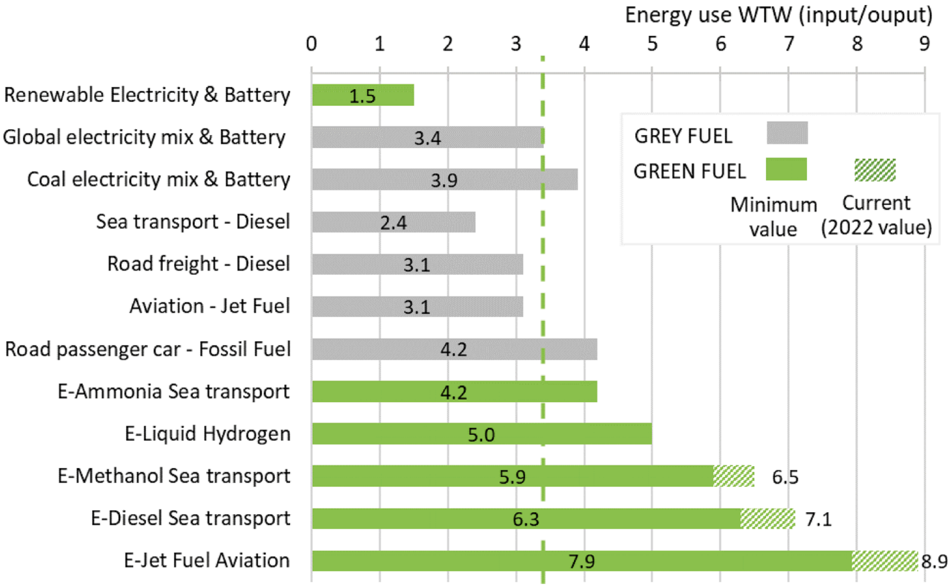

Fig. 5. WTW Energy use as a function of fuel and transport mode.

cars which will be scrapped over the coming years.

The bottom five green bars represent liquid fuels produced from renewable electricity with characteristics similar to their fossil counterparts. The WTW factors for these electro-fuels vary from 4.2 for E-Ammonia up to 7.1 for E-diesel if used on a ship with 50 % engine efficiency (Lindstad et al., 2021). If the E-diesel or E-Jet fuel instead is used on truck or an aircraft, the WTW factors deteriorate further to 8.9, due to the lower engine combustion efficiency. The high WTW figures for the E-fuels are mainly explained by an energy loss of around 30 % when electricity is converted to hydrogen, in addition to 20 to 50 % of the remaining energy used for further processing into E-ammonia, E-Methanol, and E-diesel or for compressing or liquefying the hydrogen itself so that it can be stored and transported. It should here be noted that in the literature there is a large spread in values published for the efficiency of electrolysers and that IEA (2019) published values in the range from 56 to 81 % today which improves to 63 – 84 % in 2030. For sensitivity analysis it's easy to see that using very low efficiency values, i.e., high losses increase the E-fuels WTW values as displayed in Fig. 5 too even higher levels and contrary even with the highest efficiencies their WTW values are higher than for the fossil fuels and much higher than for the electric and battery combinations.

To sum up, our findings show that for passenger and road freight, the best E-fuel option is E-hydrogen in combination with a fuel cell, with a WTW energy use of 4.5 based on compressed hydrogen and 5 if it comes in the form of liquified hydrogen. For aviation it is E-Jet Fuel with a WTW energy use of 8.9; For maritime the best option is to use a combination of E-ammonia, E-Hydrogen in liquid form, E-Methanol, E-Diesel and even E-LNG (not shown in the figures) which will give a WTW energy use of around 5. Finally for rail, it is similar to road, and it should be based on hydrogen and fuel cells, i.e., 5.

Based on published literature, it can certainly be argued that the Well to Wake (or energy system) efficiency for these and similar options are somewhat higher or lower. A brief sensitivity analysis has therefore been performed, to assess the impact from higher and lower assumed thermal combustion efficiencies of the fossil options. The results as presented in the sensitivity section show that while it directly influences the amounts of renewables needed, it makes only marginal difference for the comparisons and main conclusions.

The main observations from Fig. 5 are: First that renewable electricity in combination with batteries gives the lowest energy use measured WTW; Second that the global electricity mix in combination with batteries gives higher energy use WTW than its pure fossil counterparts applied in sea-transport, aviation, and road freight, but gives and a marginal reduction compared to road passenger car, i. e., 4.1 versus 4.2. Third, compared to fossil fuels the liquid or gaseous E-fuels raises energy consumption from 75 % with E-ammonia (4.2 versus 2.4 for diesel in sea transport) up to nearly 200 % with E-diesel (7.1 versus 2.4 for diesel) in sea transport and E-Jet Fuel applied in Aviation (8.9 versus 3.1).

4.3. WTW CO_2 emissions within the transport sector

In Fig. 6, the WTW energy use is replaced by the WTW CO_2 emissions per kWh. We then assume that renewable electricity does not produce any GHG emissions Well-to-Wake. Compared to a full Life cycle assessment, our Well-to-Wake assessment excludes the production and the montage of the windmills, solar panel parks and hydro power stations, the required supply grid, the de-montage at end of-production and final disposal. For the global electricity mix we use 556 g of CO_2 per kWh from Table 2, which with conversion loss factor of 1.225 (loss factor for the car/vehicle, excluding grid loss), gives 681 g CO_2 per kWh when combined with an electric motor and a battery on a transport carrier. In the case of coal-based electricity, the WTW emissions becomes $1131*1.225 = 1385gCO_2/kWh$.

For sea transport with conventional fuels (Diesel or Very low sulphur Fuel oil) we use 654 g per kWh (104 + 541 + 9 = 654) based on Lindstad et al (2020). For Road freight and Aviation, we use 817 (130 + 676 + 11), simply using the sea transport figure with a lower engine efficiency, i.e., 40 % instead of 50 %. Similarly, for passenger road transport, the sea transport figure increase from 654 to 1090 g per kWh due to 30 % engine efficiency compared to 50 % with sea transport. For the E-fuels, assuming from 100 % renewables and limiting the scope to WTW, we only get some TTW emissions of CH_4 and N_2O. The detailed dataset is available in Annex 1.

Combining Fig. 5 and Fig. 6 enables us to estimate the total Global WTW energy use and CO_2 emissions for four alternative scenarios: First, that we continue AS IS with a nearly 100 % use of fossil fuels; Second, that we fully replace the fossil fuels with gaseous or liquid E-fuels; Third, that we make the transport sector fully electric in combination with batteries; Fourth, that we go for the best use of renewables within the transport sector, i.e. using the renewable energy where we get the largest emission reductions per renewable energy unit used and inversely, not using it when it increases energy use WTW compared to its current fossil counterparts.

The main observations from Table 2 are as follows: First: if continued AS IS the transport sector will use 149EJ WTW. Second: if replacing fossil fuels with gaseous or liquid E-fuels, WTW energy consumption increases by more than 60 % from 149 to 240EJ, also raising global primary energy use by around 15 %; Third, if it one day is possible fully to electrify with transport with renewables in combination with batteries, total transport WTW energy use falls by 60 % from 149EJ to 66EJ. However, with the current limitations regarding battery storage capacity, renewable electricity can only play a minor role within Aviation and Sea Transport, such as for shorter flights and shorter sea crossing. New battery ferries across fjords, are now replacing the older diesel ones in Norway. To conclude, the results indicate that a wise use of renewables in the transport sector first gradually electrifies passenger car transport and second freight transport when larger amounts of renewables become available. Aviation and deep-sea transport continue with the existing fossil fuels. If fully implemented, that will reduce WTW energy use with nearly 50 % from 149EJ to 80EJ, and WTW GHG

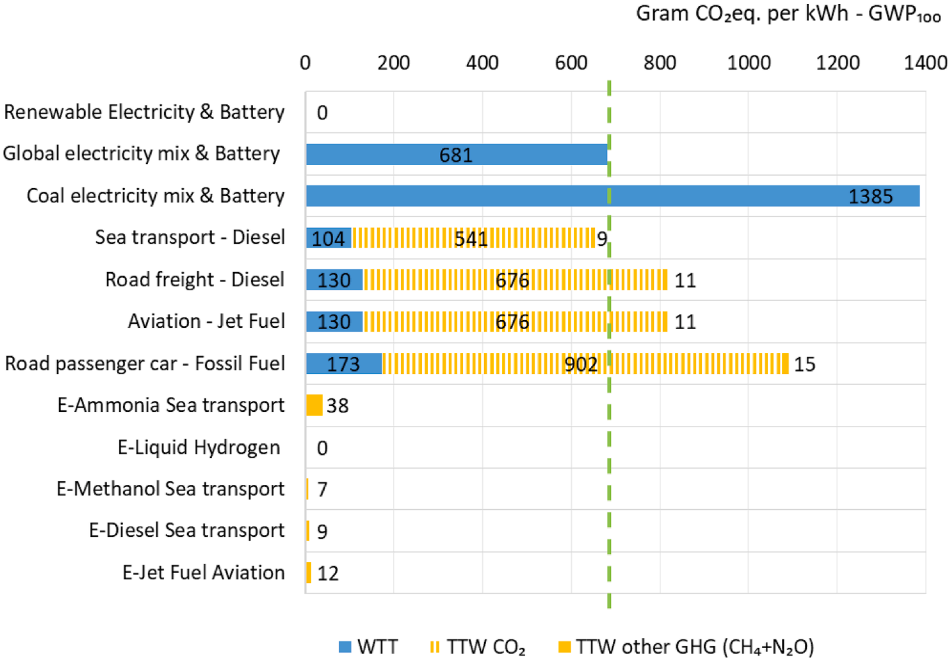

Fig. 6. WTW GHG emissions as a function of fuel and transport mode.

Table 2
CO2 abatement per Energy unit of renewable, for distinct renewable-based options and per transport segment.

	Road		Aviation		Maritime		Rail		Total
	Pas-senger	Freight	Pas-senger	Freight	Pas-senger	Freight	Pas-senger	Freight	
TTW (EJ)	55.1	37.0	9.9	2.8	1.0	10.6	0.8	1.6	119
WTW (EJ)	68.9	46.2	12.4	3.6	1.3	13.3	1.0	1.9	149
WTW energy use (input/output)									
Today	**4.2**	**3.1**	**3.1**	**3.1**	**2.4**	**2.4**	**2.0**	**2.0**	
E-Fuels	5.0	5.0	8.9	8.9	5.0	5.0	5.0	5.0	
Electric & Battery AS IS	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	
Electric & Battery Green	**1.5**	**1.5**	1.5	1.5	1.5	1.5	**1.5**	**1.5**	
WTW total energy (EJ)									
AS IS	**69**	**46**	**12**	**4**	**1**	**13**	**1**	**2**	**149**
Gaseous and Liquid E-Fuels	82.1	74.5	35.5	10.2	2.6	27.7	2.5	4.8	240
Electric & Battery AS IS	67.3	61.1	16.4	4.7	2.2	22.7	2.1	4.0	180
Electric & Battery Green	24.6	22.4	6.0	1.7	0.8	8.3	0.8	1.5	66
Best use of Fossil			**12.4**	**3.6**	**1.3**	**13.3**			**31.0**
Best use of Renewables	**24.6**	**22.4**					**0.8**	**1.5**	**49.2**
WTW million ton of CO_2eq.									
AS IS	**5 268**	**3 531**	**948**	**272**	**97**	**1 015**	**39**	**74**	**11 244**
With E-Fuels	0	0	0	0	0	0	0	0	0
Electric & Battery AS IS	3 359	3 604	967	278	124	1 294	39	74	9 740
Electric & Battery Green	0	0	0	0	0	0	0	0	0
Best use of Renewables	**0**	**0**	**948**	**272**	**97**	**1 015**	**0**	**0**	**2 332**

emissions with around 80 %, from 11 244 to 2 332 million tons of CO_2 eq. To achieve such a reduction, 49EJ of new renewable energy production must be delivered, including electrification of rail in addition to road. This selective electrification still requires a great increase in renewable generation compared to the 6–7 EJ in new annual renewable electricity production up to 2050 as foreseen in the Net Zero by 2050 by IEA (2021) and the Sky scenario by Shell (2021).

4.4. *Maximizing global GHG reductions through wise use of renewable electricity*

With the anticipated non-relenting shortage of renewable energy up to 2050, a key question is therefore: can we get larger GHG reductions if we use the renewable energy in other sectors than transport, or how to use the renewable electricity that becomes available most wisely within the transport sector. If we exclude primary energy used for industrial products (the non-energy use), the transport sector and the electricity generation account for more than 60 % of Global energy use measured WTW. We therefore limit ourselves to assessing how we can get the largest GHG reductions by optimizing the renewable energy use within energy generation

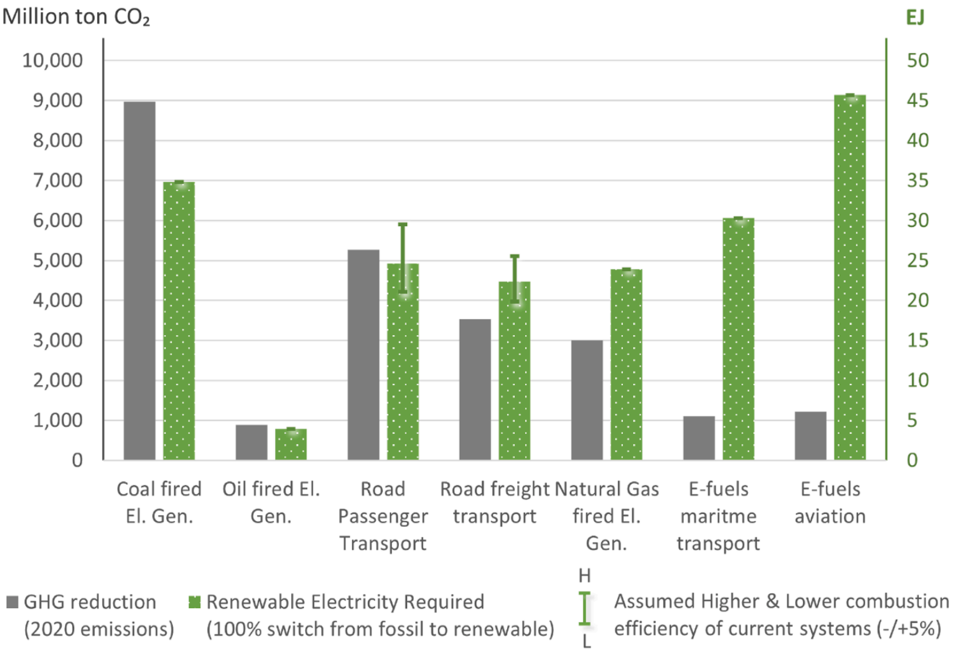

Fig. 7. GHG reduction and renewable energy required for distinct use of renewable electricity.

and the transport sector seen as a total. Combining Table 1 and Table 2 enables us to assess total CO_2 reduction as a function of renewable energy use as shown in Fig. 7. The first grey bar shows total GHG emissions in million tons and the patterned green bar shows required renewable energy in EJ to fully decarbonize (See Fig. 8).

The main observations are: First, replacing coal in the electricity generation gives the largest GHG reduction, i.e., nearly 9 billion tons CO_2, requiring 28.55EJ/0.82 = 34.8 EJ of new renewable electricity and a GHG reduction of 258 million ton per EJ. The 0.82 is based on the Well to Tank conversion losses for renewables given by Table1; Second, electrifying Road passenger transport gives the second largest GHG reduction i.e., 5.3 billion tons, which requires 24.6EJ and gives a GHG reduction of 215 million tons per EJ; Third, electrifying Road freight transport gives the third largest GHG reduction, i.e., 3.5 billion tons, which requires 22.4 EJ, and gives a GHG reduction of 158 million tons per EJ. Fourth, replacing natural gas with renewables in the electricity production gives the fourth largest GHG reduction, i.e., 3 billion tons of CO_2, which requires 19.6EJ/0.82 = 23.9EJ (based on the same conversions as for coal) and gives a GHG reduction of 126 million tons of CO_2 per EJ; Fifth replacing oil in electricity production gives a high GHG reduction per EJ, i.e., 224 million tons of CO_2 per EJ, however this way of producing electricity are mostly for remote and developing areas and hence harder to abate. Sixth, decarbonizing aviation through zero-carbon fuels reduces emissions with only 1.2 billion ton of CO_2 and requires 45EJ, i.e., more than road passenger and freight and gives only 27million ton of CO_2 in reduction per EJ compared to 258 by replacing coal in the electricity generation. Seventh, decarbonizing maritime transport through zero-carbon fuels reduces emissions with only 1.1 billion ton of CO_2 requires 30.2EJ, i.e., nearly the same amount as required for replacing coal with renewables and which gives 37million ton of CO_2 in reduction per EJ compared to the 258 by replacing coal in the electricity generation. To summarize this implies that we get 6 to 10 times larger CO_2 reduction per energy unit of new renewable electricity by replacing coal fired electricity production and electrifying passenger and road freight than using renewable electricity on zero carbon fuels for aviation and maritime transport.

A key question to ask, is how robust these values and recommendations are regarding variations in engine efficiency of the combustion engines used in road transport, since previous published literature have used both lower and higher relative values. A sensitivity analysis is therefore performed by varying the thermal efficiency with 5 % up or down (here 5 % means 5 % out of 100 % engine) for both passenger and freight road transport while retaining the energy efficiency of electric motors and batteries unchanged. For aviation and maritime the thermal combustion efficiency will be the same both for the fossil and their zero carbon counterparts (gaseous and liquid E-fuels). For Passenger Road transport, the sensitivity test involved implied to let the thermal combustion efficiency vary between 25 % and 35 %; For road transport it implied to vary it between 35 and 45 %.

The main observations from the sensitivity analysis of road passenger and road transport: First that with a high thermal combustion efficiency, i.e. that we get more energy for propulsion out of each energy unit we will use more renewable energy to replace each unit of the fossil fuel and we will hence will get les CO_2 savings out of each unit of renewables spent; Second with a lower combustion efficiency we will due to the same logic get a larger CO_2 reduction out of each unit of renewable spent.

5. Conclusions

To mitigate climate change, a rapid de-carbonization of the transport sector is often seen as a necessity. That view is strongly advocated by the International Energy Agency in their Net Zero by 2050 scenario. Conversely, Shell's Sky scenario of Net Zero by 2070 gives priority to picking the lowest hanging fruits, all sectors considered, and hence a much slower de-carbonization of the transport sector. With these divergent views, our motivation for performing this study was therefor to investigate how the transport sector and each of its sub-sectors can best use renewable electricity, and inversely, when that renewable electricity is better used elsewhere to reduce Global GHG emissions. The main finding at the literature review stage was that insufficient attention is given to the impact of transport sectors' decarbonization measures on the energy production sector, that cross-sectoral studies are needed, and these should focus on how to best use renewable energy when all sectors are chasing zero GHG emissions. This motivated us further to investigate how new renewable energy, a scarce resource when all sectors will try to de-carbonize before 2050, could be used most wisely within the transport sector or alternatively within the energy sector. Our results stress that priority up to 2050 should be: First, to use new renewable energy to replace coal fired electricity production to nearly decarbonize the electricity grid because that gives the largest decarbonisation per unit of renewable energy; Second, to gradually electrify road transport; Third, continued use of fossil fuel in shipping and aviation, because if the 1.5°target shall be met, we cannot afford to make liquid or gaseous E-fuels which gives 5 to 10 times less decarbonisation per unit of renewable energy compared to replacing coal or in road transport. Our results are heavily relying on the assumptions taken on decarbonization pathways and on the feasibility and potential of mitigations scenarios. In the future, more studies based on energy systems modelling, could give the possibility to better account for the fact that the different segments of the economy have their own dynamic, costs of replacements and retrofits and that a comprehensive evaluation on the wise use of renewable energy should consider a more global and economic perspective.

CRediT authorship contribution statement

Elizabeth Lindstad: Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft. **Tor Øyvind Ask:** Investigation, Validation. **Pierre Cariou:** Investigation, Supervision. **Gunnar S. Eskeland:** Validation. **Agathe Rialland:** Funding acquisition, Project administration, Writing – original draft, Methodology, Visualization.

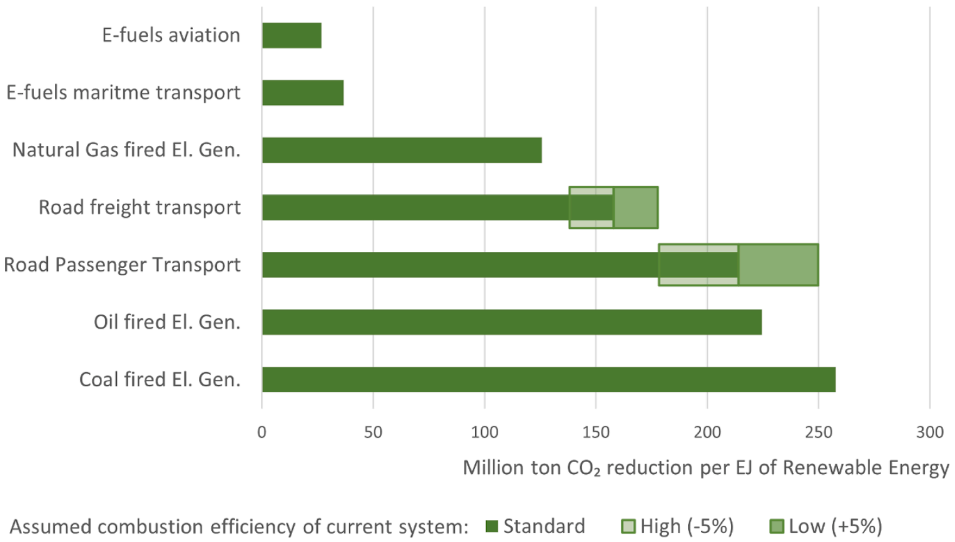

Fig. 8. Sensitivity analysis - Million-ton CO_2 reduction per EJ of Renewable Energy - for various % of thermal combustion efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

			GHG Emissions per MJ					Thermal engine or System efficiency	GHG Emissions per kWh	Energy Usage	
Fuel	Engine Type	LCV	WTT	TTW CO2	TTW CH4	TTW N2O	WTW	TTW	WTW	TTW Input / Power Output	WTW Input / Power Output
Unit		*Mj/ kg*	*g CO2e/ MJ – 100 yrs*					*%*	*gCO2e/kWh – 100yrs*	*unit/unit*	
Renewable Electricity & Battery	Electric		0	0	0	0	0	80 %	0	1.2	1.5
Global Electricity mix & Battery	Electric		154	0	0	0	154	80 %	681	1.2	3.4
Coal Electricity mix & Battery	Electric		314				314	80 %	1385	1.2	3.9
Sea transport - Diesel	Diesel	42.7	14.4	75.2	0.2	1.1	90.9	50 %	654	2.0	2.4
Road freight - Fuel	Diesel	42.7	14.4	75.2	0.2	1.1	90.9	40 %	817	2.5	3.1

(continued on next page)

(*continued*)

			GHG Emissions per MJ					Thermal engine or System efficiency	**GHG Emissions per kWh**	**Energy Usage**	
Fuel	Engine Type	LCV	WTT	TTW CO2	TTW CH4	TTW N2O	WTW	TTW	WTW	TTW Input / Power Output	WTW Input / Power Output
Aviation - Jet Fuel	Jet Engines	42.7	14.4	75.2	0.2	1.1	90.9	40 %	817	2.5	3.1
Road passenger car - Fuel (1)	Diesel & Petrol	42.7	14.4	75.2	0.2	1.1	90.9	30 %	1090	3.3	4.2
E-Ammonia Sea transport	Dual Fuel Diesel	18.6	0	0	0	5.3	5.3	50 %	38	2.0	4.2
E-Liquid Hydrogen	Fuel Cell	120.0	0	0	0	0	0	50 %	0	2.0	5.0
E-Methanol Sea transport	Dual Fuel Diesel	19.9	0	0	0.2	0.7	0.9	50 %	6	2.0	6.5
E-Diesel Sea transport	Diesel	42.7	0	0	0.2	1.1	1.3	50 %	9	2.0	7.1
E-Jet Fuel Aviation	Jet Engines	42.7	0	0	0.2	1.1	1.3	40 %	12	2.5	8.9

(1) Diesel values are used as a proxy; thermal engine efficiency reflects the average for all newer cars.

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