Battery-Electric vs. Hydrogen: Modeling the decarbonization pathways and environmental trade-offs of global road freight

Citation for the original published paper (version of record):
Kanchiralla, F., de Oliveira Laurin, M., Brynolf, S. et al (2026). Battery-Electric vs. Hydrogen: Modeling the decarbonization pathways and environmental trade-offs of global road freight. Advances in Applied Energy, 22.
http://dx.doi.org/10.1016/j.adapen.2026.100278

Advances in Applied Energy 22 (2026) 100278

Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen

Battery-Electric vs. Hydrogen: Modeling the decarbonization pathways and environmental trade-offs of global road freight

Fayas Malik Kanchiralla *, Maria de Oliveira Laurin, Selma Brynolf, Maria Grahn

Department of Environmental and Energy Sciences, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

ARTICLE INFO

Keywords:
Trucks
LCA
Energy system model
Driving range
Learning curve
Integrated assessment
Sector-coupling

ABSTRACT

Road freight accounts for 40% of global transport CO_2 emissions and is a major source of urban air pollution. This study aims to explore future role of battery-electric and hydrogen technologies for different truck segments considering driving choice, payload, and cost development, and environmental implications of this transition. The study uses novel integrated global energy systems modeling and life cycle assessment capturing truck energy transition considering cross-sectoral resource availability and systematic sensitivity of technology adoption to cost-learning rates. The results show that battery-electric trucks will dominate road freight, mainly regional delivery, reaching 70% of total transport work by 2050 in ambitious climate scenarios, leveraging superior efficiency, whereas hydrogen use is only 10% of total transport work, limited to long-haul operations. Hydrogen is most cost-effectively used in complement with batteries using fuel cell range extended electric vehicles where operational cost balances with the high investment cost of batteries. Road freight decarbonization is delayed by power sector decarbonization, indicating renewable electricity expansion as a critical enabler. Zero emission vehicles have 10% slower adoption under current national commitment compared to the more ambitious climate scenario. This indicates the need for direct policy support for road freight decarbonization linked to power sector planning. Rapid decline in battery cost shows 10% increase in battery-electric vehicle adoption and decreases the role of hydrogen in road freight decarbonization. The transition comes with environmental co-benefits, including about 75% reduction of particulate matter formation, acidification, and eutrophication. Environmental tradeoffs include metals and mineral depletion as well as land use.

Introduction

Road freight transport is a growing area of focus for reducing transportation-related fossil fuel consumption and greenhouse gas (GHG) emissions as this accounts for approximately 40 % of global transportation carbon dioxide (CO_2) emissions [1]. Between 2000 and 2020, global road freight transport GHG emissions increased by over 50 %, driven by economic growth, increased freight demand, and predominantly reliance on diesel and gasoline [2]. Along with GHG emission, fossil fuel use also affects human health due to substantial emissions of various air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM), and sulfur oxides (SO_X) [3]. Mitigating these environmental impacts involves improving energy efficiency and transitioning to low- or zero-emission technology, which has been shown to substantially reduce air pollutant emissions and associated health impacts [4]. Given the significant correlation between road freight activity and economic growth [5], increased freight activity would increase emissions and to meet the climate target, the transition is essential. Unlike passenger cars, road freight is considered a sector hard to abate [6] due to challenges such as longer daily operational ranges, specific payload requirement, limited downtime for refueling/charging, increased energy demand, cost-sensitive operation, and fragmented ownership model [7]. Transitioning these vehicles to zero-emission alternatives requires considering critical operational characteristics, including driving range, payload capacity, energy storage volume, and power-weight ratio, which impose distinct constraints on the suitability of battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) technology in the freight segments [8].

Within different alternative strategies, BEVs and FCEVs offer the most promising technology pathways as zero-emission vehicles (ZEVs) with many multi-national manufacturers already offering models with both technologies [9]. However, the conditions under which each technology is cost effective and environmentally beneficial remain uncertain due to higher vehicle cost, regional variations in electric grid

---

* Corresponding author.
E-mail address: fayas.kanchiralla@chalmers.se (F.M. Kanchiralla).

https://doi.org/10.1016/j.adapen.2026.100278
Received 16 March 2026; Received in revised form 1 May 2026; Accepted 1 May 2026

carbon intensity, operational feasibility considering driving range, availability of renewable hydrogen, charging/refueling challenges, and difference in total cost of ownership across operational contexts. Several studies have examined the role of BEVs and FCEVs in road freight decarbonization from both system and technology perspective. Çabukoglu et al. [10] analyzed the potential of FCEVs in decarbonizing Switzerland's road transport and display greater technical potential due to their extended range. Giuliano et al. [11] indicate that BEVs are restricted by charging and range limitations for short-term and higher adoption depending on improved battery efficiency and reduction in costs, and their study underscores the improvement of BEVs in recent years. Nykvist and Olsson [12] analyzed the feasibility of BEVs in heavy duty road freight and concluded that BEVs could be competitive with optimal battery cost and also with fast charging implementation. Lajevardi et al. [13] analyzed the GHG emissions and mitigation costs of zero-emission vehicles, including BEVs and FCEVs, compared to traditional drivetrains. Hannula et al. [14] show that BEVs are likely to remain more expensive than carbon-neutral synthetic fuels under certain assumptions. A recent comprehensive review across China, Europe, and the United States [15] confirmed that while BEV can achieve 27–58 % lifecycle CO_2 reductions relative to diesel, FCEV face a persistent cost disadvantage due to hydrogen accessibility.

A common limitation of these studies is that they treat road freight as a standalone system, thereby overlooking cross-sectoral interactions. Emissions reduction benefits from using BEVs and FCEVs depend on the carbon intensity of the electricity grid and the hydrogen production routes [16], and the carbon intensity is not fixed but evolves over time with broader energy system transitions. Moreover, all sectors compete for the same globally limited resources, including biomass and renewable electricity, making it essential to model road freight decarbonization within a framework that endogenizes these interactions [17]. Sector-coupled energy system optimization models (ESOMs) facilitate such analysis, capturing energy transition dynamics across various sectors [18]. Global and long-term models with regional disaggregation are particularly valuable, given that carbon intensities of electricity and hydrogen production vary dramatically across geographies and evolve at different rates. Speizer et al. [17] have analyzed global transportation, including road, rail, and aviation, using an integrated assessment tool (Global Change Analysis model v6.0) for the 'sustainability' scenario on Shared Socioeconomic Pathways (SSP), considering emission constraints that ensure global warming below 1.5 °C· The results from the study underline the importance of both BEVs and FCEVs for road freight transport decarbonization, however the representation of road freight in the model is aggregated and hence does not consider different driving range and the freight capacity. Combining cross-sectoral interaction with life cycle assessment is critical to understanding the overall environmental performance of road freight transition, a gap in existing studies.

Another gap in the literature concerns the geographic and operational granularity of ESOM-based road freight studies. While several national-level ESOMs have examined different truck segments including studies for Denmark [19], Ireland [20], India [21], China [22], and Sweden [23], global perspective remains rare. Mulholland et al. [24] is one of the few studies that has considered the freight segments from a global perspective, but it does not account for cross-sectoral interdependence. A similar segmented analysis for China [25] also omits cross-sectoral interdependence. Studies that capture the sectoral interdependence, such as analysis of hydrogen-power sector interaction in Germany [26] and global transport modeling [17] do not combine this with detailed disaggregation of truck segments and driving range requirements. To our knowledge, no existing study combines global multi-segment road freight disaggregation, cross-sectoral ESOM, cost learning curve sensitivity analysis, and integrated prospective LCA within a single framework.

Our study addresses these three gaps directly. First, it provides a globally disaggregated, sector-coupled ESOM analysis of road freight decarbonization that includes details on truck segments and driving profiles while endogenizing cross-sectoral competition for energy resources. Second, it systematically quantifies sensitivity of BEV and FCEV adoption trajectories respond to varying technology cost learning rates for batteries and hydrogen technologies within a global optimization framework. Third, it integrates prospective LCA in ESOMs that cover well-to-wheel environmental impacts beyond climate impact, also accounting for the temporal evolution of the background energy system.

The Global Energy Transition (GET) model v12 is used for the assessment, which is a sector-coupled, global, bottom-up energy system model with 10 different geographic regions. GET v12 is specifically configured to assess the three truck segments (LCV- light commercial vehicles, MDT- medium duty trucks, and HDT- heavy duty trucks) assuming two driving profiles (regional-delivery and long-haul) tailored to the distinct attributes of each category. Along with the transition, we also assume energy improvement, including energy intensity reduction, activity improvement, and load utilization of freight transport. The model optimizes the total cost throughout the entire energy system, in all regions and time steps, subject to several constraints where the CO_2 reduction targets are represented with a global carbon budget. The model is integrated with life cycle assessment (LCA) that allows us to understand well-to-wheel (WtW) environmental impacts related to transport, including direct emissions, embodied energy, fuel infrastructure, fugitive emissions, land use, and process emissions. The study analyzes five scenarios: 1) SSP1RCP19 – 'sustainability' scenario and representative concentration pathway 1.9 W/m^2; 2) SSP2RCP26 – 'middle of the road' scenario and representative concentration pathway 2.6 W/m^2; 3) SSP2NDC – 'middle of the road' scenario and Nationally Determined Contribution based on countries' climate pledges also considering peak warning below 2 °C; 4) SSP2RCP34 – 'middle of the road' scenario and representative concentration pathway 3.4 W/m^2; 5) SSP3RCP45 – 'Regional Rivalry' scenario and representative concentration pathway 4.5 W/m^2. Furthermore, the study analyzes the effect of applying low-cost learning curves to hydrogen and batteries, respectively, and details of the costs are provided in the Supplementary Information (SI).

Methods

Global energy transition model

GET v12 is a sector-coupled mathematical model for global ESOM (linear programming) that employs a bottom-up approach and operates at 10-year intervals. The model minimizes the total cost of the system by optimizing the primary energy supply between regions and expanding capacities for energy generation, energy conversion, energy storage, and transmission, while fulfilling the energy demands of different sectors and adhering to carbon budgets. GET is a deterministic model with mathematical equations that produces the same output from a given set of inputs every time, as it operates on fixed rules without randomness. The objective function of the model is to find the lowest cost solution to meet the energy demand of end use sectors, under different constraints and assumptions over the modeled time horizon (Eq. (1)).

$$\mathit{Total\ System\ Cost} = \sum_{reg,t} \frac{t_{step} * \mathit{Annual\ Cost}_{(reg,t)}}{(1+r)^{t_{step}*(ORD(t)-1)}} \tag{1}$$

Where, $\mathit{Annual\ Cost}_{(reg,t)}$ is sum of different costs for different regions (reg) and each time period (t) as shown in Eq. (2). This includes primary energy costs ($\mathit{Energy}_{cost(reg,t)}$), technology and infrastructure investment costs ($\mathit{Invest}_{cost(reg,t)}$), fixed and variable operation and maintenance costs ($\mathit{OM}_{cost(reg,t)}$), and carbon storage cost, (Eq. (2)). There are ten different regions, and the time horizon is 2010–2150 with timesteps of ten years and discounted relative to the reference year (2010). More details on the temporal and geographical scope of the model are given in SI Section S1.1.

$$\begin{aligned} Annual\ Cost_{(reg,t)} &= Energy_{cost(reg,t)} + Invest_{cost(reg,t)} + OM_{cost(reg,t)} \\ &\quad + Dist_{cost(reg,t)} + Carbon_{cost(reg,t)} \end{aligned} \tag{2}$$

The GET v12 comprises ten modules (Fig. 1): primary energy supply; energy conversion and storage; carbon capture; energy export and import, energy distribution; carbon budget and emission conversion; the electricity sector (incorporating time slices for regional variable renewable energy conditions); the transport sector; industrial feedstocks; and the heat sector. In the model, primary energy sources (crude oil, natural gas, coal, nuclear, hydro, biomass, wind, and solar) are converted into various energy carriers to satisfy the energy demands of end-use sectors. The technical and economic relationships between technologies are parameterized using efficiency, load factors, costs, and lifetimes. The model includes several constraints such as annual or total supply limits on available energy sources; expansion constraints for investments; load balance equilibrium; CO_2 budgets; limitation on export and import (e.g., electricity); and permanent CO_2-storage capacity availability. More details of each module are available in SI, Section S1.2.

This work has introduced GET v12 as a refinement of GET v11 [18] where details specifically adapted to road freight transport modules are modified by introducing three segments (LCV, MDT, and HDT) and two driving profiles (regional-delivery and long-haul) as shown in Fig. 2. In the study, LCV refers to commercial vehicles with gross vehicle weight (GVW) <3.5 tonnes, MDT represents commercial vehicles with GVW between 3.5 tonnes and 15 tonnes, and HDT represents commercial vehicles with GVW greater than 15 tonnes. Regional-delivery is referred to as trips that have daily operational ranges of <500 km and others are referred to as long-haul. All mathematical formulations and other modules are derived from GET v11, which is detailed in [18], and data used are listed in the SI.

The GDP, population and demand forecasts for all sectors, excluding transport, in various geographical regions are derived from the SSP scenarios of the IIASA GGI Scenario Database [27]. Transport demand scenarios of road, rail and aviation for different SSP scenarios are taken from GET v10 [28]. The transport demand for shipping is taken from the GET v11 and is detailed in [29], following the methods in the Fourth IMO GHG Study [30]. Road freight transport activity in the model was projected using the econometric framework developed by Mulholland et al. [24] based on the empirical relationships between freight activity, economic development, population, and regional characteristics. The methodology uses a multivariate log-linear regression model to predict

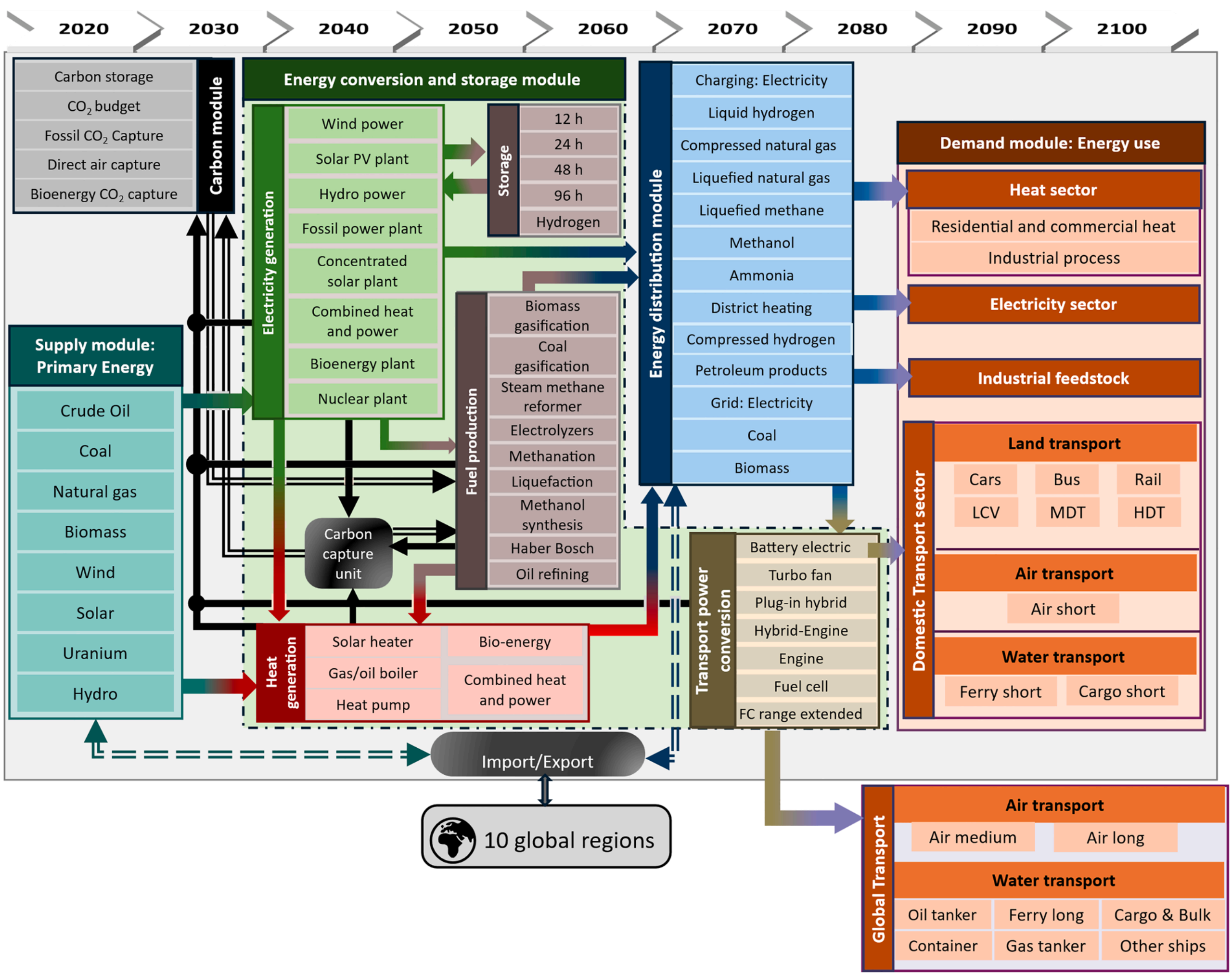

Fig. 1. Simplified structure of the Global Energy Transition (GET) model v12, illustrating the linkages between primary energy supply, energy conversion and storage, carbon capture, and end-use demand sectors including transport, industry, and heat across ten geographic regions. The model minimizes the total system cost by optimizing the primary energy supply across regions, and expanding capacities on energy conversion, energy storage, and distribution, while fulfilling the energy demands of different sectors and adhering to carbon budgets. The major processes relevant to each section included in the GET model are also shown. Carbon flows are accounted by considering carbon capture technology in energy conversion step and also carbon storage with overall carbon budget. The carbon budget is considered until 2100 and also the technology evolution is considered over different decades. LCV- light commercial vehicles, MDT- medium duty trucks, and HDT- heavy duty trucks.

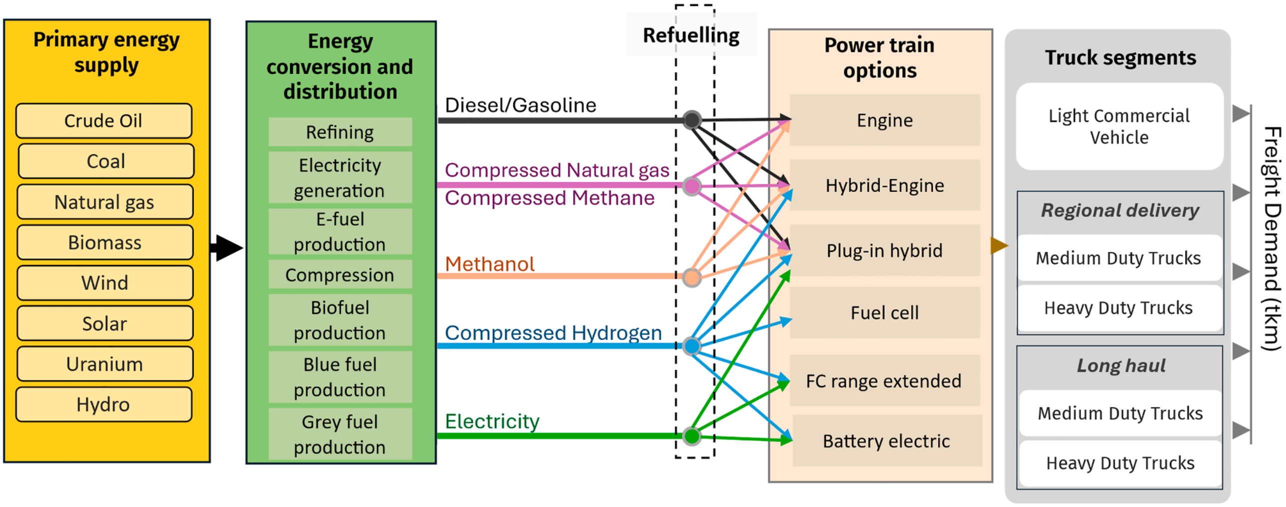

Fig. 2. Simplified structure of the road freight module in GET v12, illustrating the pathways from primary energy supply through energy conversion and distribution, refuelling infrastructure, and powertrain options to the modelled truck segments. Truck segments are disaggregated into Light Commercial Vehicles (LCV), and Medium Duty Trucks (MDT) and Heavy Duty Trucks (HDT) under two driving profiles — regional-delivery (daily range <500 km) and long-haul (daily range ≥500 km). Methanol is a proxy for non-fossil-based synthetic liquid fuels such as biofuels and e-fuels.

the freight activity measured in tonne-km and vehicle-km. These are then converted to energy demand for different truck size allocation, load factor estimation, and fuel efficiency assumptions. The log-linear regression equation used is shown in Eq. (3) and separate regressions are run for HDT and MDT with truck specific coefficient from Mulholland et al. [24]. Details of the data used are in SI.

$$\ln\left(FD_{r,t,k}\right) = \beta_{0,k} + \beta_{1,k}.\ln\left(\frac{GDP_{r,t}}{POP_{r,t}}\right) + \beta_{2,k}.NFP_{r,t} + \beta_{3,k}.SF_{r,t} \tag{3}$$

Where, FD: freight demand (million tonnes-km), GDP: Gross domestic product (USD), POP: population, NFP: normalized fuel price index, SF: Size factor for each region (binary), k: vehicle segment, r: region, and t: time period. NFP and SF are regional specific parameters, where SF means that the region area is larger reflecting longer shipping distances and different freight patterns. Regional fuel price indices were constructed to reflect differences in taxation, subsidies, and energy policy across regions. The baseline values were set to 1.0 for Europe, with adjustments for other regions based on Mulholland et al. [24]. The energy demand for the freight is calculated using Eq. (4).

$$E_{i,r,k,t} = \sum_{i} FD_{r,t,k}.I_{r,t,k}.\eta_i \tag{4}$$

Where E is energy demand, i is the fuel-powertrain technology, I is the intensity of energy in MJ/tkm for the diesel powertrain technology, η_i is the efficiency ratio between the fuel-powertrain type and the diesel powertrain technology. The energy intensity is assumed to improve over decades based on the IEA modern truck scenario reaching highest efficiency (other than powertrain) by 2050 [5]. The weight load factor for projecting each segment is used for the number of vehicles in the model. These data are limited and the assumptions for the average load factor (tonnes per vehicle) are also based on Mulholland et al. [24] and are estimated as functions of GDP per capita, reflecting changes in logistics efficiency and vehicle utilization patterns with economic development. However, it may be noted that there is great uncertainty in these data especially in developing regions.

There are different projections of the cost of battery technologies and hydrogen technologies. The cost assumptions in this study are based on the cost learning curves mentioned in Link et al. [31]. The Link et al. study used meta-forecast involving regression analysis. For the base case, cross-category projection is used, and for the low-cost scenario, the lowest cost expectation category is used. In the low-cost battery case, it is assumed that the cost of the battery pack will decrease faster and reach USD 70/kWh by 2050 compared to the base case of USD 100/kWh. In the low-cost hydrogen case, it is assumed that the cost of hydrogen fuel cells is USD 75/kW and the cost of compressed hydrogen tanks USD 2500/GJ compared to the base case of USD 100/kW and USD 3500/GJ, respectively. For more details, see Link et al. [31]. An additional sensitivity assessment is performed considering the different storage requirements for the given daily driving range, assuming that the trucks are charged when they arrive at the depot or the drivers take breaks. The cost sensitivity is performed using Eq. (5) by varying the battery cost, and hydrogen technology cost, respectively. The driving range is varied for the sensitivity analysis, where different storage requirements are varied.

$$\begin{aligned} C_{inv,vtype} = {} & C_{base,vtype} + BC \times \frac{DR_{vtype} \times ER_{vtype}}{ER_{el} \times DOD \times 3.6} + FS \times \frac{DR_{vtype} \times ER_{vtype}}{ER_{fuel} \times 1000} \\ & + PC \times P_{fc,vtype} \end{aligned} \tag{5}$$

The costs are calculated separately for each vehicle category (*vtype*) and added to the investment cost in Eq. (2). Where C_{base} is base investment cost without considering battery cost, fuel storage cost and powertrain cost. These are calculated in the later part of the equation including a battery cost term comprising battery cost per unit energy (*BC*, USD/kWh) scaled by the battery share of driving range (α_b), driving range (*DR*, km), energy consumption (*EC*, MJ/km), electrical efficiency ratio (ER_{el}), and depth of discharge (*DOD*), a fuel storage cost term comprising fuel storage cost per unit energy (*FS*, USD/GJ) scaled by the fuel share of driving range (α_f), and a powertrain cost term comprising fuel cell/engine cost per unit power (*PC*, USD/kW) and the installed power (P_{fc}, kW).

The possibility of battery swapping and electric charging roads are not considered in the model. The rate of utilization of the charging infrastructure varies from seasonal to monthly temporal resolution and is also disaggregated by type of powertrain [32], neither of which is considered in the model. Another limitation of the model is that several real-world technology adoption constraints are excluded, e.g., technology lock-in effects where early investments create path dependencies, learning curve advantages for technologies deployed sooner, and the additional costs associated with being first-movers in unproven technologies. The biomass potential (in total 134 EJ/yr) in the model is limited to the sources that can be extracted in a sustainable way, including sources rich in lignin & cellulose, starch & sugar, used cooking oil, as well as rest-flows & waste from agriculture, forestry and society, e.g., straw, sawdust, manure, sludge, animal fats and food waste; however, only one conversion pathway based on gasification is chosen as proxy for all biomass conversions.

Another limitation is that the assumed maximum long-term carbon storage capacity (600 million tonnes of CO_2) is modelled as one global storage, equally accessible from all regions, with geological carbon sequestration and infrastructure for CO_2 transport, assumed to expand at similar rates as carbon capture technologies in the model. Both batteries and fuel cells degrade over time; however, we have disregarded the efficiency, storage capacity, or power decline over time. The applicability of the model is mainly to understand the long-term energy transition and does not capture short-term changes. Energy carriers and fuel costs including electricity and hydrogen that are used to meet the demand of end-use sectors are fully endogenous to the model, e.g., The cost of compressed hydrogen is generated based on the optimal investment decision on all the investment needed for the conversion of primary energy to the final end use like electricity generation infrastructure, electrolyzer, distribution infrastructure, compression facility, etc. Consequently, the price of hydrogen fuel reflects the optimal system cost of electrolytic hydrogen in each scenario and region, rather than an externally assumed price trajectory. This endogeneity is important to interpret the results of fuel adoption with respect to the expansion of the fuel production infrastructure and the availability of primary energy.

Integration of LCA and GET

To evaluate the broader environmental impacts of energy transition, it is essential to employ a methodology that encompasses fuel infrastructure, resource extraction, and additional emissions, while also accounting for temporal variations in the energy system over various time steps. The prospective LCA is more appropriate than the attribution technique for forward-looking assessments [33], as it preserves temporal consistency with the evolution of energy systems. Consequently, in this study, pLCA calculations are performed as post-processing to evaluate the environmental implications of various combinations of fuel and propulsion for road freight within the scenarios analyzed. Since the depth of the technology description is much more detailed in the pLCA, the pLCA is integrated into GET in various steps and WtW analysis is performed in the postprocessing step. The integration approach ensures that the key parameters, such as efficiency, in GET are harmonized with the process-specific pLCA in terms of energy flows.

The functional unit of the assessment is the total road freight transport work for each time step, which is different for each scenario. The system boundary includes the impacts associated with energy extraction, fuel production, fuel infrastructure, indirect changes in land use, fuel combustion, and fugitive emissions. The temporal framework from 2020 to 2100 is incorporated into the process-specific LCAs using time-specific characteristics from the GET model for around 90 processes that are directly and indirectly associated with road freight. Inventory data for LCA are modified to prevent double counting of the effects on downstream energy system supply chains, with the analysis being carried out gate-to-gate. This entails nullifying the energy inputs of LCI processes, as these inputs are already delineated as separate processes within the GET model. The impacts related to the energy input are incorporated after the analysis of the energy mix derived from the GET output. The life cycle inventory (LCI) predominantly depends on process-oriented data derived from previous research; this is listed in SI, Section S4.1 [34–36] and uses the pLCA data set (premise) v1.5.8 tool [37] with background data from ecoinvent v3.10 [38]. Premise v1.5.8 [37] is used to include the time-dependent sectoral transformation of the infrastructure, materials and embodied energy, and this temporal development is based on the IMAGE model [39] considering scenarios from the SSP and RCP assumptions [40].

Environmental impacts are assessed for seven midpoint impact categories: climate impact, PM formation, terrestrial acidification, marine eutrophication, land use, resource use – fossil, and resource use – metals and minerals. All environmental impacts other than the climate impact are estimated based on EF 3.0 [41] and climate impact is estimated using the global warming potential over 100 years based on IPCC AR6 [42].

Results

Truck fleet energy transition

Fig. 3 shows the adoption of technology for transport work corresponding to the energy transition of the road freight fleet including LCV, MDT-RD, MDT-LH, HDT-RD and HDT-LH across three scenarios until 2080. Only one (SSP2NDC) out of three 'middle of the road' scenarios is presented, since the results are similar, detailed results for the other scenarios are given in SI, Section S3. As depicted in Fig. 3, the adoption of technology varies with scenario stringency and the segment of the vehicle. In the most ambitious SSP1RCP19 scenario, ZEV adoption dominates with 80 % of total road freight transport work (10 % hydrogen and 70 % electricity) by 2050 and 100 % adoption of ZEV by 2080 (20 % hydrogen and 80 % electricity). Regional-delivery has the largest ZEV adoption, mainly dominated by BEVs with 80 % and 90 % for HDT and MDT, respectively, by 2050. Hybrid technologies play a transitional role, reaching a peak share of 15 % of total transport work before being replaced by BEVs. Compared to the HDT and MDT segments, the LCV has prolonged use of fossil fuels; this is the result of the model's least cost logic in the model for a maximum reduction of emissions. The model prioritizes the investment in MDT and HDT due to their higher annual fuel consumption per vehicle compared to LCV. Higher annual fuel means higher utilization of the investment that gives maximum reduction potential for a given decarbonization investment (i.e., a lower total cost is achieved when investments are made in segments where utilization is high, and thus fossil use is phased out at a faster pace).

In stark contrast to the ambitious scenario (SSP1RCP19), the road scenario assuming current policies (SSP2NDC) yields 70 % ZEV penetration of total road freight transport work across all segments by 2050 (10 % lower). The same can be observed for other 'middle of the road' scenarios with a slight delay in the transition under RCP3.4 W/m^2 (SI Section S3). In these scenarios, 3 % of the total freight transport will still rely on fossil fuels by 2080. Under the regional rivalry scenario with less focus on carbon mitigation (SSP3RCP45), only 20 % penetration of ZEV can be observed by 2050 and 25 % of the total road freight transport is dependent on fossil fuel by 2080.

A significantly faster adoption rate of BEVs compared to hydrogen technologies can be observed for road freight transport in all scenarios (Fig. 3). Under the most ambitious climate scenario, BEVs surge from a low share in 2030 to 70 % of total transport work by 2050, whereas hydrogen technologies capture only 10 % of total transport work by 2050; this is because batteries meet operational requirements with high overall energy efficiency, unlike hydrogen which have high energy losses during hydrogen production and powertrain conversion. These high energy losses increase the operating cost; in addition to high operation cost, the investment cost for hydrogen technologies including refueling, fuel cells and storage, is also high. Even under current policies (SSP2NDC), more than 60 % penetration of BEVs in road freight transport by 2050, demonstrating that BEVs may play the most important role in road freight decarbonization in all scenarios. Larger adoption can be observed for HDT compared to the MDT segment, because HDT has high energy usage, for a given distance, and since BEVs offer superior energy efficiency, the operational cost reduction is high for HDT. This is specifically noticeable for the regional-delivery operation profile.

There are differences in the adoption of technology for regional-delivery and long-haul freight operations, revealing distinct energy transition pathways shaped by operational requirements. The adoption

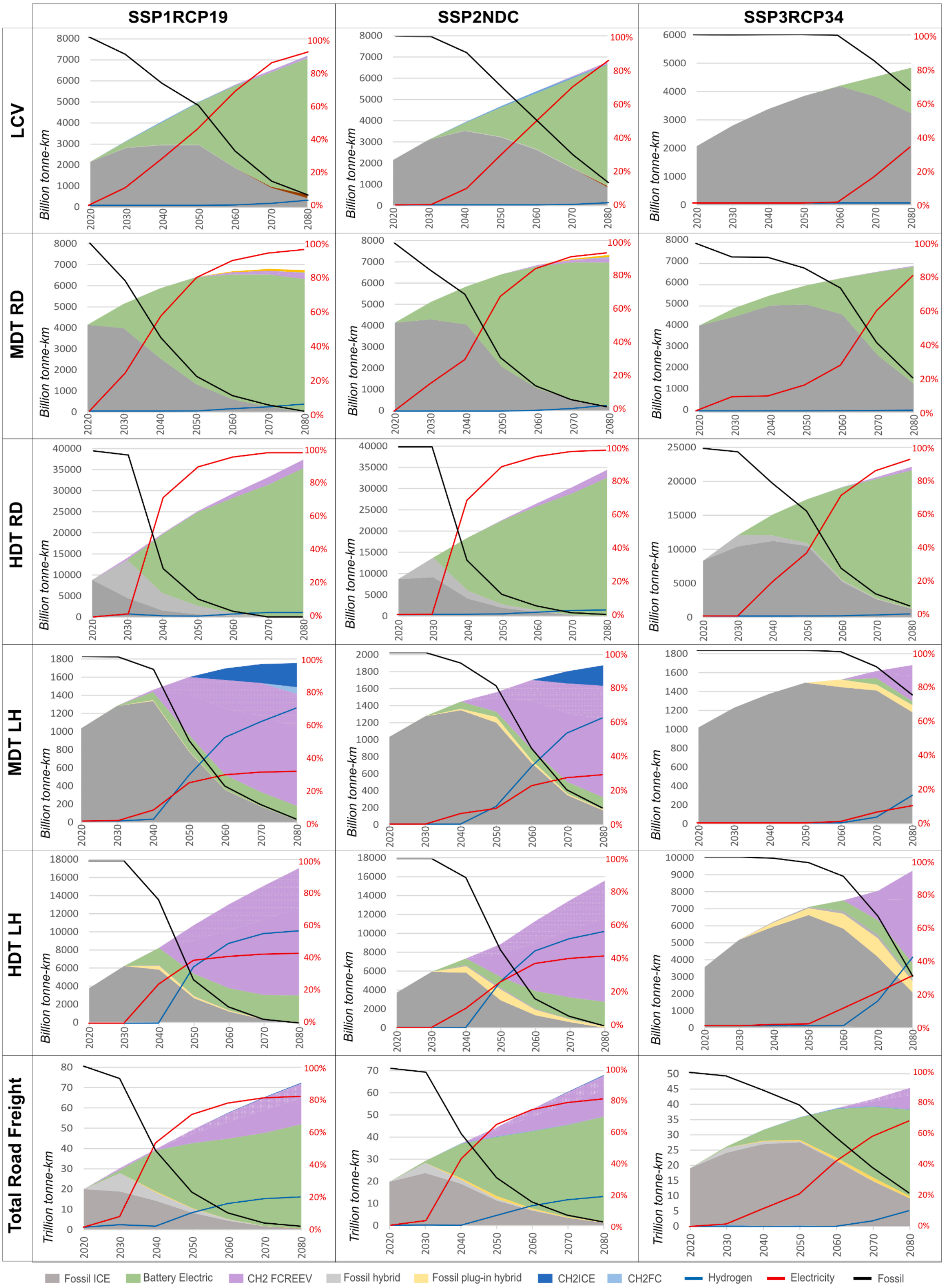

Fig. 3. Technology adoption of technology and the energy share pathways for total road freight transport in scenarios and vehicle segments. Colored areas show transport work in billion tonne-km by fuel/technology type (left axis); red, blue, and black lines show electricity share, hydrogen share, and fossil fuel share, respectively (right axis). LCV: Light Commercial Vehicles, MDT: Medium Duty Trucks, HDT: Heavy Duty Trucks, RD: Regional-Delivery, LH: Long-Haul. SSP1–ambitious climate scenario, SSP2–middle of the road, SSP3–regional rivalry. RCP: representative concentration pathway, NDC: Nationally Determined Contribution, ICE: internal combustion engine, CH2: compressed hydrogen, FCREEV: fuel cell range extended electric vehicles.

rate is slower for long-haul operations compared to regional-delivery applications. Regional-delivery operations characterized by predictable routes and moderate daily ranges of <500 km and depot charging opportunities exhibit rapid battery electrification in all scenarios. Regional-delivery has very low adoption of the hydrogen-related powertrain system (< 5 %) in all scenarios. In the ambitious climate scenario, the adoption of BEVs reaches 80 % for MDT and 90 % for HDT by 2050 for regional-delivery. In the middle of the road scenario, BEV adoption reaches around 70 % and 85 % for MDT and HDT, respectively.

In contrast to the regional-delivery operation, hydrogen plays an important role in the decarbonization of long-haul operations, which are defined by daily ranges exceeding 500 km. This segment is mainly dominated by FCREEVs that use hydrogen and electricity. This means that both electrification and hydrogen play a role in long-haul operations. The adoption of FCREEVs in long-haul operations is expected to reach 40 % for MDT and 50 % for HDT by 2050. By 2080, the adoption of FCREEVs will reach 70 % for MDT and 80 % for HDT applications. The role of fuel cell electric vehicles (FCEVs) is limited in all applications; this is due to the high investment cost and operational cost of FCEVs. Although FCREEVs have high investment costs compared to FCEVs, the operational efficiency savings from additional battery investment reduced the operational cost of FCREEVs. The higher cost of the investment of FC is also due to the oversizing required for FC so that fuel cells do not operate above 60 %. This oversizing is necessary to reduce degradation, and FCs have the same service life as ICE trucks. Hydrogen in ICE is also adopted for the long-haul application of MDT (15 %) by 2080. This shows that the complementary role of hydrogen and batteries may be significant for long-haul trucks, whereas regional-delivery may be dominated by BEVs.

Cost scenario analysis

Adoption of a certain technology also depends on how the different costs of batteries, fuel cells, and hydrogen tanks, would develop over time. Fig. 4 shows technology adoption across three cost learning curve scenarios: 1) baseline case with optimal cost reduction for both technologies, 2) low-cost battery case, where the cost of the battery pack decreases faster than baseline (reaching USD 70/kWh by 2050 vs USD 100/kWh in the baseline), and 3) low-cost hydrogen case, where hydrogen fuel cell cost (reaching USD 75 / kW vs. baseline USD 100/kW) and compressed hydrogen tank cost (reaching USD 2500/GJ by 2050 vs. baseline USD 3500/GJ). In the low-cost battery case, a

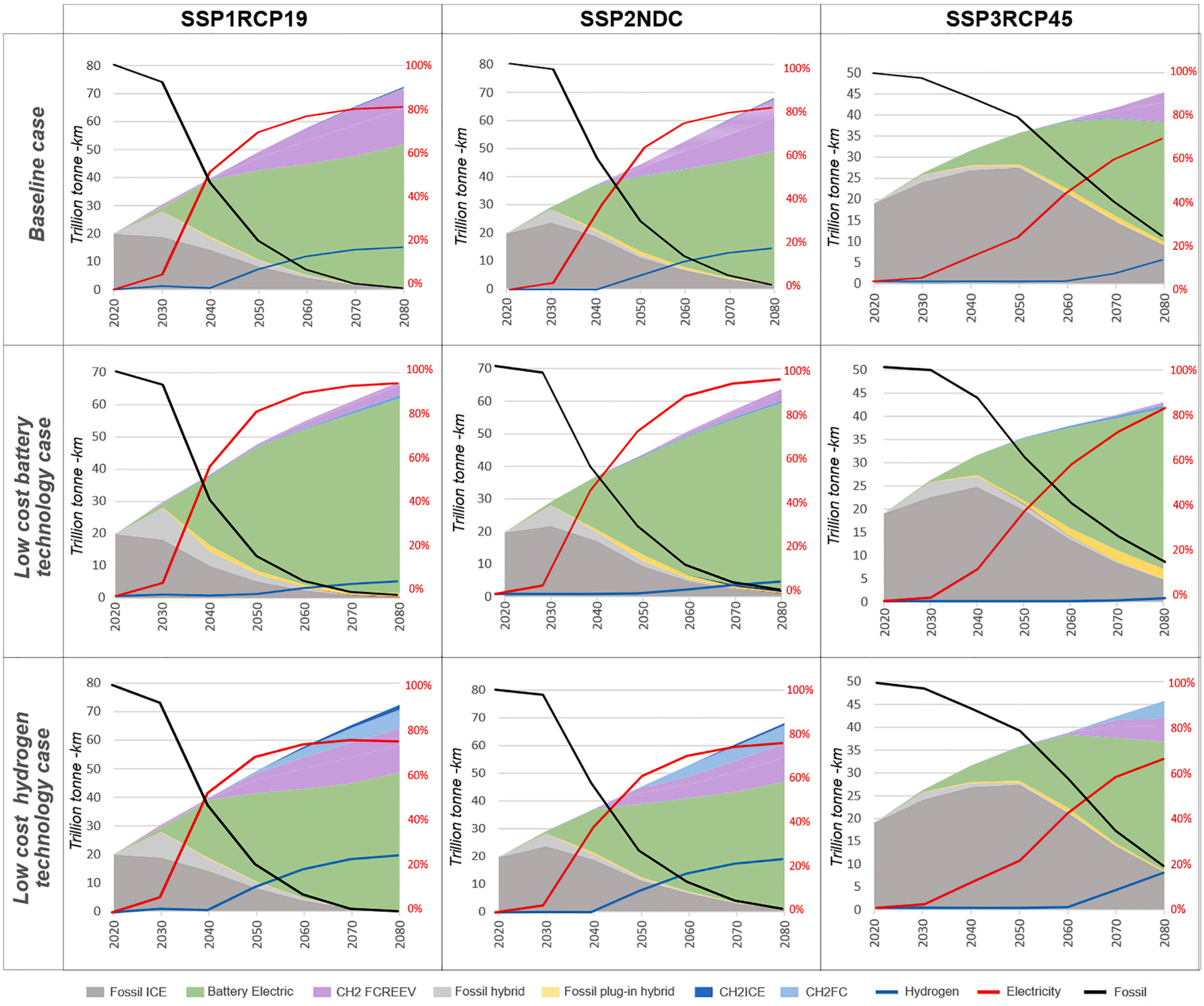

Fig. 4. Technology adoption under different cost expectations of batteries and hydrogen technologies for total road freight transport under three climate scenarios. Colored areas show transport work in billion tonne-km by fuel/technology type (left axis); red, blue, and black lines show electricity share, hydrogen share, and fossil fuel share, respectively (right axis). SSP1–ambitious climate scenario, SSP2–middle of the road, SSP3–regional rivalry, RCP: representative concentration pathway, NDC: Nationally Determined Contribution, ICE: internal combustion engine, CH2: compressed hydrogen, FCREEV: fuel cell range extended electric vehicles.

significantly accelerated adoption of BEVs can be observed in all climate scenarios. Under the scenarios SSP1RCP19 and SSP2NDC, electrification contributes to 95 % of total transport work, an increase of 10 % compared to baseline by 2080. A 15 % increase in electrification can be observed in the case of the SSP3RCP45 (regional rivalry) scenario. It can be noted that there is more than 10 % decrease in hydrogen use, this indicates that the applications favoring FCREEVs, shift towards BEVs as battery cost is decreased. This indicates that hydrogen trucks play a low role in decarbonization of freight if the battery cost falls and are limited only to have extended range. However, in the low-cost hydrogen case, the increase in hydrogen deployment, especially FCEVs, is modest compared to baseline. This modest adoption of FCEVs mainly replaces the adoption of FCREEVs in long-haul operation (see SI, Figure S2). This suggests that the cost improvement in hydrogen vehicles is not sufficient for larger adoption. Larger adoption may require availability of low-cost hydrogen fuel, which is challenging because of the high energy losses in the electrolyzers and supply chain. The low battery cost and low-cost hydrogen scenarios also indirectly represent policies where investment support to reduce the cost of these technologies, implying that subsidies help speed up the adoption rate of ZEVs for road freight.

Energy carriers and pathways

The level of decarbonization in road transport is related to the decarbonization of other sectors, since the total emissions of both hydrogen and electricity depend on the upstream production. That is, the new demand for renewable electricity production comes from electrification and hydrogen use in road freight. Fig. 5 shows the supply chain and total primary energy demand, at 20-years intervals, showing the interdependence between road freight decarbonization and other sector transformation, especially electricity generation and hydrogen production. Fossil fuels can be substituted with a lower cost in the stationary energy sector, compared to the transport sector. Even if transport work increases with time, the energy demand for total road freight decreases over the decades due to the higher efficiency of BEVs and FCREEVs compared to conventional diesel/gasoline engines. Some of these reductions are also attributable to enhanced design and operational efficiency, which is exogenously modeled in GET.

The large investment in renewables (solar and wind) in the power sector can be observed in the power sector post 2030 (Fig. 6). This opens up the way for the use of fossil-free electricity and electrolytically produced hydrogen (here denoted e-hydrogen) in the transport sector, as shown in Fig. 5. Electricity for both charging and production of e-hydrogen is mainly from solar power and wind power with a small share of nuclear and other non-fossils. Although biofuel generation methods are incorporated into the model, it favors the utilization of biomass mainly in the industrial sector and aviation, rather than in road transport. This is due to the limited supply potential of biomass, making it economically viable to allocate it to industries where high heat is required along with bioenergy carbon capture and storage (BECCS).

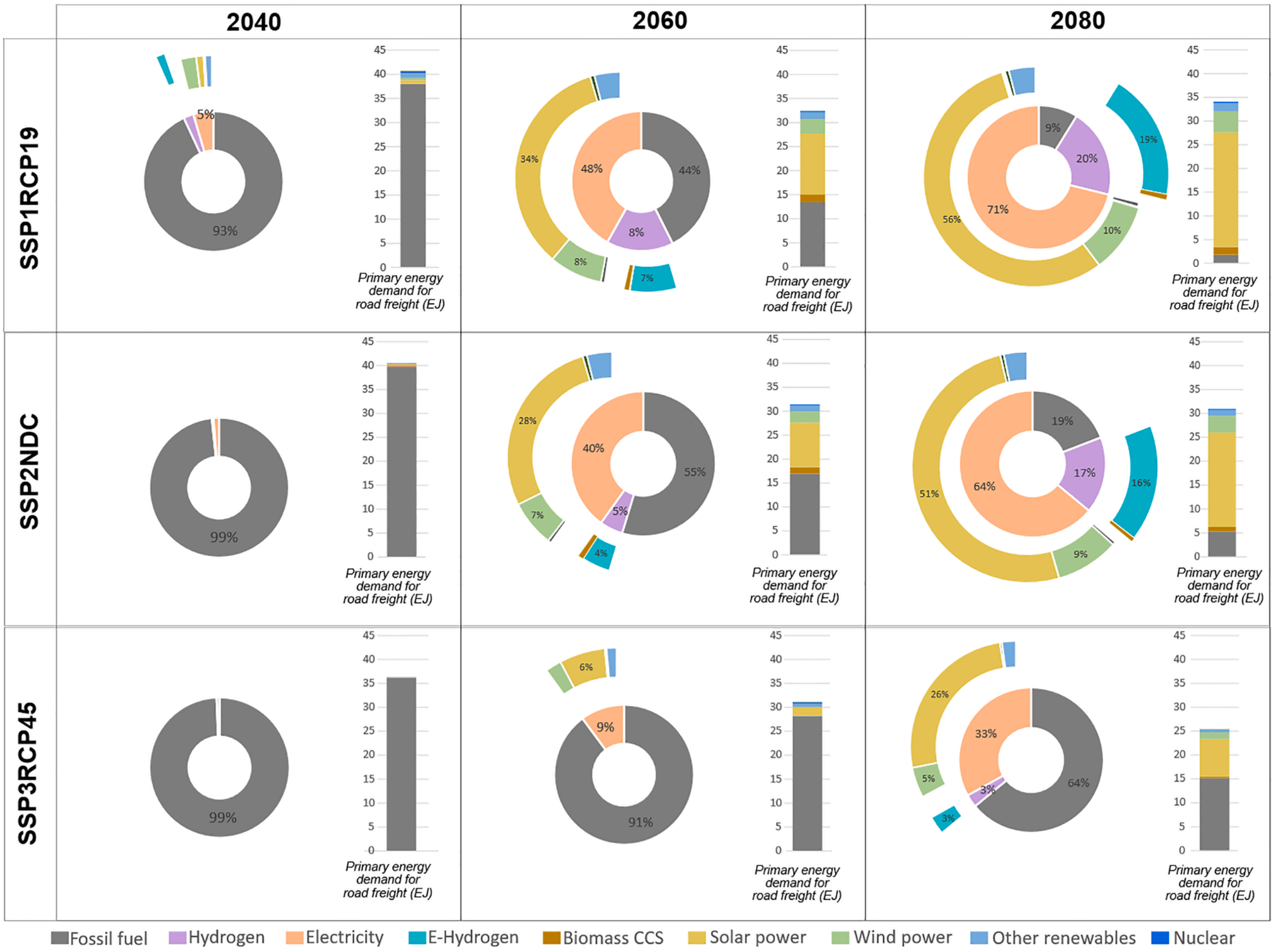

Fig. 5. Energy carriers that supply the road freight in three climate scenarios for 2040, 2060, and 2080. Results show the profound interdependence between road freight decarbonization and broader energy system transformation. Inner circle shows the share of energy required for the road transport, outer circle shows the distribution of electricity generation and hydrogen production, respectively. The bar plot shows the total primary energy demand (EJ) for including the energy required for electricity production, hydrogen production, and fossil fuel refining. CCS: carbon capture and storage, SSP1–ambitious climate scenario, SSP2–middle of the road, SSP3–regional rivalry, RCP: representative concentration pathway, NDC: Nationally Determined Contribution.

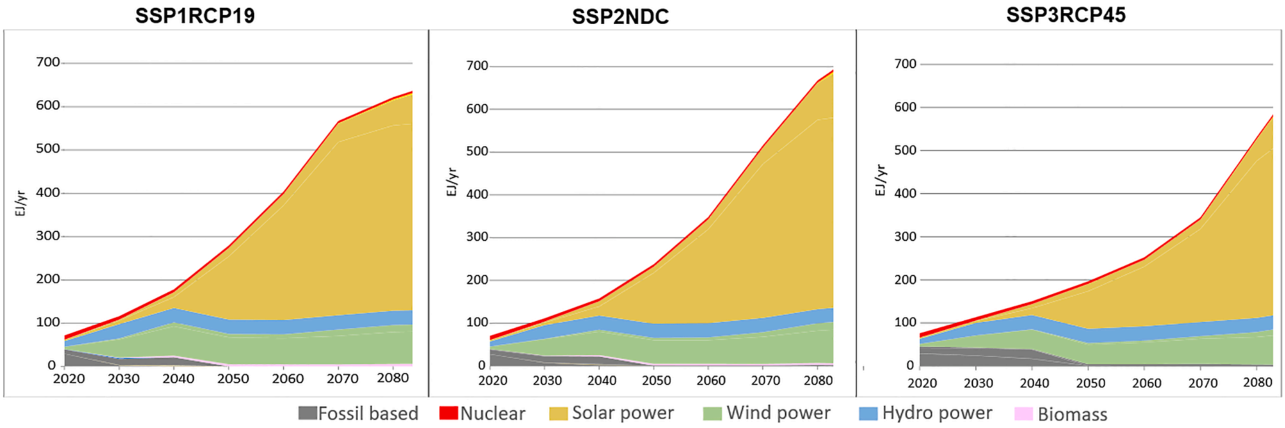

Fig. 6. The transition of power sector in three climate scenarios from 2020 to 2080. This transition result shows the sector-coupling between transport and power sectors, and the need for renewables to meet the electricity demand, e.g. driven by the decarbonization of the heavy duty transport sector.

BECCS can have negative GHG emissions and thus used to offset emissions from other technologies where abatement is costly. The model show use of biofuels in aviation, as high energy dense fuels produced from a non-fossil source, is specifically important for aviation decarbonization.

Environmental impacts of energy transition

Fig. 7 illustrates the environmental impacts of road freight energy transition in the three scenarios (SSP1RCP19 – ambitious climate scenario, SSP2NDC – present scenario, and SSP3RCP45 – regional rivalry), showing co-benefits and tradeoffs associated with ZEV deployment beyond direct climate mitigation. The functional unit is for total road freight transport work in different time steps. These include the WtW impacts associated with the fuel conversion emissions, fuel production, fuel infrastructure, indirect changes in land use, and fugitive emissions. Results show that climate impacts decline dramatically under SSP1RCP19 scenario, reaching nearly zero by 2080 and remaining emissions are associated with well-to-tank (WtT) mainly embedded emissions in fuel supply infrastructure. The rapid decline reflects the combined effect of the adoption of ZEVs that eliminate tailpipe emissions and decarbonization of the power sector, reducing the reduction of emissions upstream. Current policies show slower progress in climate impact reduction due to prolonged use of fossil fuels. The share of tank-to-wheel (TtW) emissions in total emissions reflects the share of diesel which peaks around 2030 is all scenarios except regional rivalry where it peaks between 2030 and 2040. Regional rivalry scenario shows significant slower progress, and a higher TtW emission share remains until 2080.

The adoption of ZEVs also shows a significant reduction (>75 %) in several impact categories, including PM formation, terrestrial acidification, marine eutrophication, and resource use (fossils). This reduction is mainly attributed to the absence of tailpipe emissions for ZEVs including NOx, SOx, PM, and CO, this can be observed in reduction in TtW emission in Fig. 7. The upstream emissions of these pollutants are also negligible as the electricity mix has high share of renewables including solar and wind and very low share of thermal power plants. This indicates that road freight decarbonization with BEVs and hydrogen technologies can deliver substantial co-benefits, improving air quality and natural environment. However, transition also comes with specific tradeoffs on environmental impacts like metals and minerals resource use as well as land use. The increase in resource use is largely attributed to the materials associated with the electrolyzers used for hydrogen production (platinum), renewable electricity generation including wind power (rare earth metals), batteries (lithium, cobalt, nickel, copper) and other infrastructures (copper). The higher impact of land use can be attributed to the share of biomass in the energy system and the larger area required for renewable electricity installations.

Sensitivity analysis

The results show that the sensitivity of the adoption of technologies depends on the choice of driving range associated with truck operation. Fig. 8 presents the sensitivity of hydrogen, electricity, and fossil fuel shares in road freight decarbonization under the SSP2NDC scenario by varying the driving range requirements revealing critical thresholds where technological competitiveness shifts. Battery electric penetration can be seen when the driving range requirement is low and the hydrogen market energy share with a higher driving range, especially by 2050–2060. The electrification shares increase significantly in the second case when the battery costs are low, especially when the daily driving range is below 800 km, the share is larger than 65 % and the share is larger than 75 % for below 600 km (the detailed quantitative value in SI, Section S3.1). These segments mainly represent regional-delivery. This also shows that market-based measures, such as subsidies on BEV investment of BEVs (resulting in lower BEV costs), can help with faster adoption of BEVs. In the cost of third scenario, when the hydrogen technology is low, share of hydrogen consumption also increases significantly but mainly in mid-range (500–1000 km). Electrification is still preferred for low-range operations in this scenario.

Discussion

The energy transition of the road freight fleet, considering different driving range and truck segments, is reviewed using global ESOM. The ESOM applied in this study not only considers different climate scenarios but also includes different cost development of ZEVs. The results show that BEVs plays a dominant role in the LCV and regional-delivery operations in MDT and HDT segments. For long-haul operations, hydrogen FCREEVs tend to play a prominent role in road freight decarbonization. FCREEVs adoption requires complementary battery and hydrogen technologies which balance the operational cost and investment cost compared to high operation of FCEVs. This finding underscores the need to optimize powertrains within hydrogen technology and to balance the battery size with installed fuel cell capacity. That is vehicle-specific energy intensity based on operation is a critical determinant of the preferred configuration. The results also reveal an interesting distinction between LCV, MDT, and HDT where HDT has a larger adoption of ZEVs. This divergence can be attributed to the lower specific fuel consumption of LCV and MDT, a consequence of their reduced weight and power requirements compared to HDT [20,24]. In HDT, higher fuel consumption means that the incremental battery investment in FCREEVs and BEVs is offset by meaningful operational efficiency gains over the vehicle lifetime, making the additional complexity and

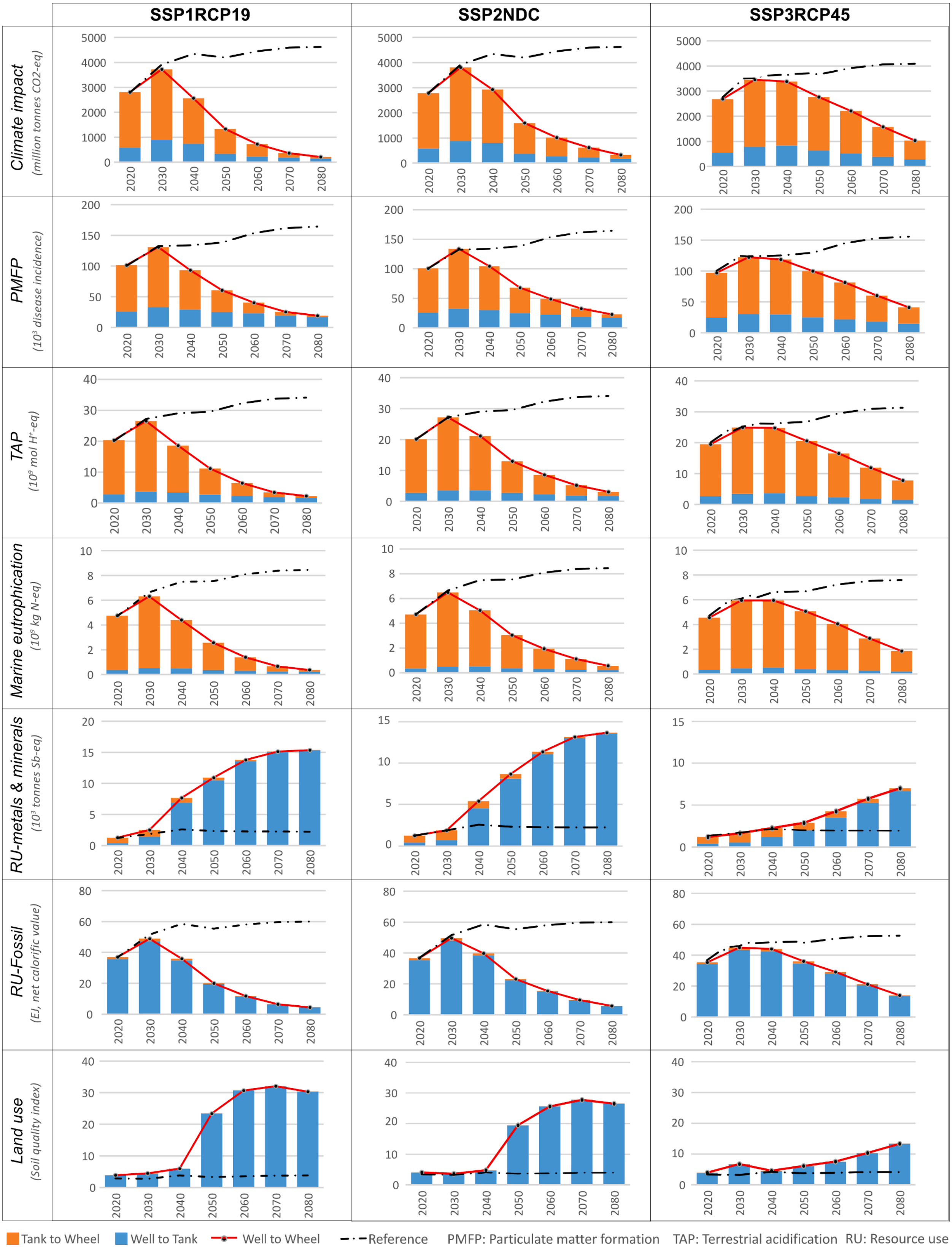

Fig. 7. Life cycle environmental impacts of the road freight energy transition under different scenarios, including climate impact, particulate matter formation potential (PMFP), terrestrial acidification potential (TAP), marine eutrophication potential (MEP), material resource use (RU-metals and minerals), fossil energy resource use (RU-fossil), and land use. SSP1–ambitious climate scenario, SSP2–middle of the road, SSP3–regional rivalry, RCP: representative concentration pathway, NDC: Nationally Determined Contribution.Reference shown is based on scenario without adoption of ZEVs (no climate targets).

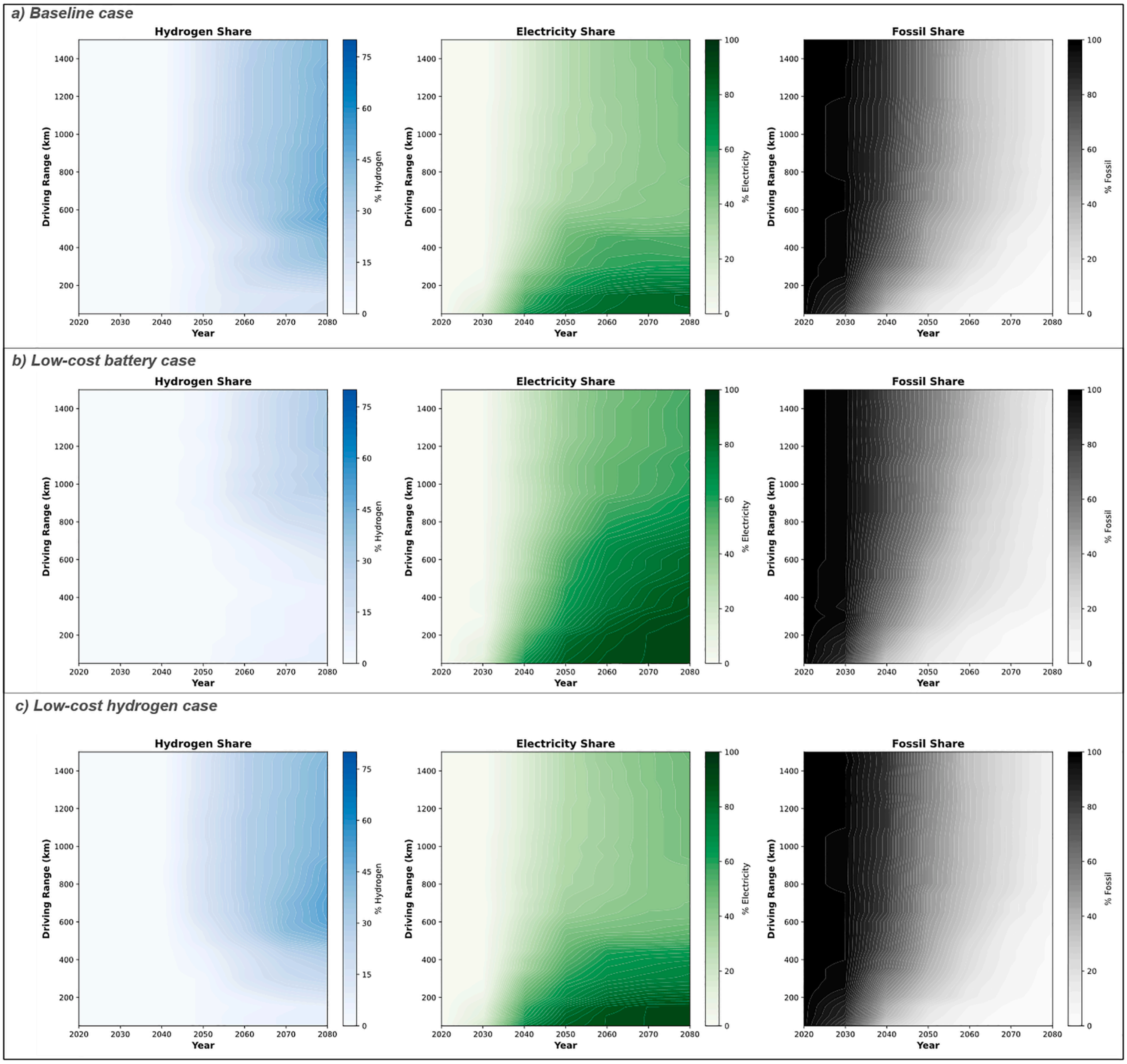

Fig. 8. Sensitivity analysis of the shares of hydrogen, electricity, and fossil fuels in road freight energy use to varying the requirements of the daily driving range in three cost learning curve scenarios: a) the baseline case, b) the low cost battery case, and c) low-cost hydrogen case. The results are based on the SSP2NDC scenario (middle of the road).

cost of the range-extended configuration worthwhile. It may also be noted that LCV segment has very diverse operations depending on purpose, ranging from private owners with limited use to courier services for last-mile logistic service [5]. This diversity makes a uniform technology pathway challenging and may be investigated separately in future studies considering this complexity. The faster adoption of BEVs, particularly for regional-delivery operations of <500 km, is attributable to their lower operational costs, which align with the investment required for comparatively smaller batteries compared to longer operating ranges. On the contrary, the benefits of operating cost do not offset the elevated investment costs of batteries designed for extended ranges, and reduce payload capacity due to low energy storage density [43].

The scenario with significantly lower battery costs reveals an important shift in the competitive boundary between battery-electric and hydrogen technologies, extending BEV viability well beyond the short-to-medium range operations that characterize their adoption under baseline cost assumptions. In the low-cost battery scenario, the investment cost penalty associated with larger battery packs required for extended range operations is substantially reduced [31]. If the battery cost learning curve follows a rapid decline, the operational domain of BEVs could expand substantially, reducing the overall role of hydrogen in road freight. On the contrary, it also implies that direct electrification will dominate road freight if the battery cost drops and the hydrogen role may be limited to range extenders, concentrating its deployment in the most demanding long-haul corridors only. This is mainly due to the higher operating cost of hydrogen trucks, driven by the cost of hydrogen fuel, hydrogen leakage in supply chain and their lower energy efficiency during the life cycle, compared to BEVs [44,45]. This cost disadvantage for FCEVs due to hydrogen fuel cost and accessibility is highlighted in different studies [15,26]. Rapid cost reduction for hydrogen powertrain technologies increases the adoption of hydrogen only to a limited extent, this also don't reduce the share of BEVs in regional delivery operation. This increase is seen mainly in the long-haul HDT segment.

It should be noted that this study does not account for potential improvements in battery energy density over the modeling horizon. Battery energy density is an important parameter that governs the penalties and range limits of BEVs, and its progress over time, given ongoing advances in cell chemistry [46], will allow the installation of higher battery storage capacity in trucks. If energy density improvements are considered along with the rapid battery cost reductions explored in the low-cost battery scenario, the BEV adoption is expected to increase further, potentially extending into the most demanding long-haul corridors and substantially diminishing the role of hydrogen in road freight decarbonization. Similarly, the possibility of battery swapping is not analyzed in the study; however, battery swapping can reduce the investment choice for high driving range trucks, which, in the sensitivity analysis shows faster adoption of BEVs. The biofuel adoption in road freight transport was absent in all scenarios mainly due to the limited potential of sustainable biomass supply. Biomass is cost-effectively used in industrial feedstock, medium and long-distance aviation (biofuel and carbon-based liquid electro-fuel), and for generating heat combined with BECCS. The same observation is found in previous studies [17,47], where the need for liquid fuels in long distance aviation, carbon-based feedstock for industries, and bioenergy with carbon capture (in process heat) is highlighted [47]. Bioenergy with carbon capture allows negative emissions when CO_2 is stored permanently, whereas when utilized for the production of carbon-based liquid electro-fuels, although it avoids fossil carbon emission during use, no negative emissions are created [48,49].

Currently, trucks fueled by natural gas can be largely seen in parts of the world, including China [22]. Natural gas is, however, not seen as a cost-effective option in any of the modeling scenarios. One reason for this is that methane leakages (stronger GHG) are assumed in the supply chain, and also engine slips, which makes this option not favorable to meet climate targets, even though they have significant lower emission of other air pollutants [50].

A limitation of the current analysis is the omission of efficiency degradation in batteries and fuel cells over their operational lifetime. In commercial fleet operations, lithium-ion battery capacity typically declines based on charging cycles and other factors, while membrane degradation of fuel cell also reduces power output over time. These effects, when integrated across a fleet replacement cycle, would increase the annualized total cost of ownership for both BEVs and FCEVs relative to the values modeled in GET v12, which assumes constant technology performance within each period. The practical implication for fleet operators is that the effective cost advantage of BEVs in regional-delivery operations may be somewhat lower than the model suggests at the fleet level, particularly in high-utilization duty cycles. Since degradation affects both technologies, their complementary roles are unlikely to change, but their impact would be different as fuel cell degradation affects the total power and battery degradation affects the total driving range.

Another important finding is that decarbonization of road freight lags behind the power sector and the use of fossil fuels continues to be cost-effective in road freight for next two decades. This is mainly because the power sector has a lower carbon abatement cost compared to the high investment costs of ZEVs. And from a cost-optimization perspective, the model minimizes total system cost across all sectors simultaneously, it prioritizes the decarbonization of the power sector first which then enables meaningful lifecycle emission reduction in transport. That is, power sector transition is critical in enabling meaningful decarbonization of transport through electrification and e-hydrogen [45]. This is because to achieve life cycle CO_2 emission reduction for electricity and hydrogen adoption, the carbon intensity of the grid has to fall below a threshold [34]. In fact, in the presence of a fossil-intensive grid, the lifecycle emissions associated with electricity generation and hydrogen production may even increase above conventional fossil fuel use [35,51].

From a policy perspective, the decarbonization of road freight requires sector-specific policies and the interdependencies with the power sector indicate that freight decarbonization strategies must be linked with the planning of the power sector, to ensure the increase in renewable capacity in anticipation of transport demand [52,53]. An emission trading system like EU ETS [54] would be one of these mechanisms that would benefit faster adoption of ZEVs due to its applicability to both the power sector and freight transport. As shown in the cost-sensitivity analysis, policy mechanisms such as cost subsidies on investment [55] will also be an effective mechanism to increase the adoption of ZEVs, especially BEVs which have high investment cost. The results reveal an important issue with Alternative Fuels Infrastructure Regulation (AFIR) in the European Union, specifically the part that mandates the deployment of hydrogen refueling infrastructure along the Trans-European Transport Network core and comprehensive corridors [56]. Under the cost-optimal transition pathways identified in this study, hydrogen plays a limited role in the decarbonization of road freight, with BEVs capturing the dominant share of the energy demand across most truck segments and driving profiles, raising a critical question about the economic justification for the hydrogen refueling infrastructure mandated under AFIR. The low share of hydrogen in road transport risks directing substantial public and private investment toward hydrogen refueling infrastructure that may be underutilized in cost-optimal decarbonization trajectories.

The transition towards ZEVs also comes with benefits for human health and the ecosystem, including reduction of impacts like PM formation, terrestrial acidification, marine eutrophication, and resource use (fossil). The reduction of these impact categories for ZEVs when used along with renewable electricity is mentioned in several individual LCA studies [16,50,57,58]. The reduction is attributed to zero tailpipe emissions of vehicles in transition scenarios and a high share of renewable electricity for charging and hydrogen production. Transition also comes with tradeoffs, mainly resource use associated material-intensive zero-emission technologies. However, these impacts can be reduced in the future with increased use of recycled materials, material substitutions, and material efficiency [58–60]. The temporal changes associated with the improvement associated with material use are not explored in this work but may be explored in future studies.

Conclusion

The study provides a comprehensive analysis on the potential roles of battery electric and hydrogen technologies in the decarbonization of global road freight, using an integrated sector-coupled energy system model that includes details on truck segments, driving profiles, and cross-sectoral competition for energy resources, combined with prospective life cycle assessment. The main finding is that battery electric vehicles dominate cost-effective decarbonization of road freight across all segments with full dominance in regional delivery operations. The hydrogen share is only about 10 % of total transport work and is mainly limited to long-haul operations through fuel cell range extended electric vehicles, where the operational efficiency savings from the supplementary battery reduces the operational cost.

The cross-sectoral result shows that road freight decarbonization is structurally dependent on the transformation of the power sector, as both electrification and green hydrogen production require low-carbon electricity. Therefore, road freight policy must be coordinated with electricity sector. Under current national commitments, ZEV adoption is approximately 10 % lower than under the ambitious scenario and full ZEV penetration by 2050 is unlikely, underscoring the need for stronger policy support. Rapid battery cost reductions can further accelerate BEV adoption by around 10 % and this further reduces the role in road freight. This shows that there is high risk for investment of hydrogen refueling infrastructures mandated in Alternative Fuels Infrastructure Regulation, due to underutilization.

Beyond climate mitigation, the transition to zero-emission vehicles delivers substantial co-benefits: particulate matter formation, terrestrial acidification, and marine eutrophication impacts reduce by over 75 %

under the ambitious climate scenario by 2080, driven by the elimination of tailpipe emissions and the high renewable share in electricity and hydrogen supply chains. However, the transition introduces tradeoffs in the use of metals and mineral resources, which require material efficiency and circular economy strategies. Achieving a cost-effective global road freight transition requires a portfolio approach that matches vehicle technology with the operational context, coordinated cross-sectoral policy that links freight and power sector planning, and sustained investment in battery cost reduction and green hydrogen production.

CRediT authorship contribution statement

Fayas Malik Kanchiralla: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria de Oliveira Laurin:** Writing – review & editing. **Selma Brynolf:** Writing – review & editing. **Maria Grahn:** Writing – review & editing, Validation, Project administration, Funding acquisition.

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.

Acknowledgement

We would like to thank Eamonn Mulholland, Senior researcher at International Council on Clean Transportation, for sharing the demand regression model for road freight. Financial support from Vinnova and the Swedish Energy Agency through the FFI Energy and Environment program funding the project ‘‘Hydrogen Engine Emissions Reduction (HEER)’’ with grant number 2020–016027 is greatly acknowledged. Thanks also to the European Union Interreg Baltic Sea Region program for funding the project ‘‘Developing a transnational network of hydrogen refueling stations for trucks (HyTruck)’’ with grant number #C031. Further, we would like to acknowledge support from the competence center Technologies and innovations for a future green Hydrogen economy (TechForH2) hosted by Chalmers University of Technology, which is financially supported by the Swedish Energy Agency (P2021-90268) and the member companies Volvo, Scania, Siemens Energy, GKN Aerospace, PowerCell, Oxeon, RISE, Stena Rederier AB, Johnson Matthey, Insplorion, and Manntek, as well as the competence center for catalysis (KCK), hosted by Chalmers University of Technology and financially supported by the Swedish Energy Agency (Project No 52689–1) and the member companies Johnson Matthey, Perstorp, PowerCell, Preem, Scania CV, Umicore, and Volvo Group. We declare no competing financial interests or conflicts that could inappropriately influence this work. We have not used generative AI or AI-assisted technologies in preparation for this work except for language check.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2026.100278.

References

[1] IEA. World energy outlook 2022. Paris.International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2022.
[2] Forum WE. Net-Zero industry tracker 2024 edition. Geneva, Switzerland: World Economic Forum; 2024 [Online]. Available, http://h.ttps/w.ww.weforum.org/publications/net-zero-industry-tracker.
[3] IPCC. Synthesis report. contribution of working groups I, ii and iii to the fifth assessment report of the intergovernmental panel on climate change. 2014. ISBN 978-92-9169-143-2, 2014.
[4] Deng R, Procházka O, Kilchert S. Life cycle assessment of future electricity and hydrogen systems: implications for low-carbon transport. Clean Environ Syst 2025;19. https://doi.org/10.1016/j.cesys.2025.100349.
[5] IEA. The future of trucks: implication for energy and the environment. Paris: International Energy Agency; 2017.
[6] IRENA. Decarbonising hard-to-abate sectors with renewables: perspectives for the G7. Abu Dhabi: International Renewable Energy Agency; 2024.
[7] WEF. High-Emitting sectors: challenges and opportunities for low-carbon suppliers. Geneva, Switzerland: World Economic Forum; 2024.
[8] Katalenich SM, Jacobson MZ. Toward battery electric and hydrogen fuel cell military vehicles for land, air, and sea. Energy 2022;254. https://doi.org/10.1016/j.energy.2022.124355.
[9] Basma H, Rodriguez F. The european heavy-duty vehicle market until 2040: analysis of decarbonization pathways. Berlin, Germany: ICCT; 2023.
[10] Çabukoglu E, Georges G, Küng L, Pareschi G, Boulouchos K. Fuel cell electric vehicles: an option to decarbonize heavy-duty transport? Results from a Swiss case-study. Transp Res Part D: Transport Environ 2019;70:35–48. https://doi.org/10.1016/j.trd.2019.03.004.
[11] Giuliano G, Dessouky M, Dexter S, Fang J, Hu S, Miller M. Heavy-duty trucks: the challenge of getting to zero. Transp Res Part D: Transport Environ 2021;93. https://doi.org/10.1016/j.trd.2021.102742.
[12] Nykvist B, Olsson O. The feasibility of heavy battery electric trucks. Joule 2021;5(4):901–13. https://doi.org/10.1016/j.joule.2021.03.007.
[13] Lajevardi SM, Axsen J, Crawford C. Simulating competition among heavy-duty zero-emissions vehicles under different infrastructure conditions. Transp Res Part D: Transport Environ 2022;106. https://doi.org/10.1016/j.trd.2022.103254.
[14] Hannula I, Reiner DM. Near-term potential of biofuels, electrofuels, and battery electric vehicles in decarbonizing road transport. Joule 2019;3(10):2390–402. https://doi.org/10.1016/j.joule.2019.08.013.
[15] Zhang S, et al. Feasibility, cost and decarbonization potential of clean pathways for heavy-duty road transportation. Nat Rev Clean Technol 2025;1(12):846–60. https://doi.org/10.1038/s44359-025-00119-0.
[16] Yang Z, Wang B, Jiao K. Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China. Energy 2020;198. https://doi.org/10.1016/j.energy.2020.117365.
[17] Speizer S, et al. Integrated assessment modeling of a zero-emissions global transportation sector. Nat Commun 2024;15(1):4439. https://doi.org/10.1038/s41467-024-48424-9.
[18] Kanchiralla FM. Energy transition towards sustainable shipping: environmental and economic life cycle considerations. Gothenburg, Sweden: Doctoral, Department of Mechanics and Maritime Sciences, Chalmers University of Technology; 2025. ISSN 0346-718X Series number: 5619.
[19] Hagos DA, Ahlgren EO. Exploring cost-effective transitions to fossil independent transportation in the future energy system of Denmark. Appl Energy 2020;261. https://doi.org/10.1016/j.apenergy.2019.114389.
[20] Aryanpur V, Rogan F. Decarbonising road freight transport: the role of zero-emission trucks and intangible costs. Sci Rep 2024;14(1):2113. https://doi.org/10.1038/s41598-024-52682-4.
[21] Dhar S, Pathak M, Shukla PR. Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario. J Clean Prod 2018;172:417–27. https://doi.org/10.1016/j.jclepro.2017.10.076.
[22] Khanna N, Lu H, Fridley D, Zhou N. Near and long-term perspectives on strategies to decarbonize China's heavy-duty trucks through 2050. Sci Rep Oct 14 2021;11(1):20414. https://doi.org/10.1038/s41598-021-99715-w.
[23] Parviziomran E, Bergqvist R. Decarbonization costs for the Swedish heavy-duty road fleet: circular economy insights on electric truck batteries. Transp Policy (Oxf) 2025;160:1–14. https://doi.org/10.1016/j.tranpol.2024.10.033.
[24] Mulholland E, Teter J, Cazzola P, McDonald Z, Ó Gallachóir BP. The long haul towards decarbonising road freight – A global assessment to 2050. Appl Energy 2018;216:678–93. https://doi.org/10.1016/j.apenergy.2018.01.058.
[25] Xue X, et al. Life cycle economic and environmental assessment for emerging heavy-duty truck powertrain technologies in China: a comparative study of battery electric, fuel cell electric, and hydrogen combustion engine trucks. Environ Sci Technol 2025;59(4):2018–30. https://doi.org/10.1021/acs.est.4c11737.
[26] Marmullaku D, et al. Quantifying hydrogen’s role in multi-sector decarbonization using price-elastic demand curves. Adv Appl Energy 2026;21. https://doi.org/10.1016/j.adapen.2026.100265.
[27] Fricko O, et al. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Glob Environ Change 2017;42:251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.
[28] Hedenus F, Karlsson S, Azar C, Sprei F. Cost-effective energy carriers for transport – The role of the energy supply system in a carbon-constrained world. Int J Hydrogen Energy 2010;35(10):4638–51. https://doi.org/10.1016/j.ijhydene.2010.02.064.
[29] Kanchiralla FM, Brynolf S, Hansson J, Grahn M. Marine fuel choices and related life cycle environmental impacts under global shipping policies. Nat Energy 2026. https://doi.org/10.1038/s41560-026-02079-6.
[30] Faber J, et al. Fourth imo ghg study. Delft: CE Delft; 2020.
[31] Link S, Stephan A, Speth D, Plötz P. Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. Nature Energy 2024;9(8):1032–9. https://doi.org/10.1038/s41560-024-01531-9.
[32] Yuan H, et al. Planning future charging infrastructure for private EVs: a city-scale assessment of demand and capacity. Adv Appl Energy 2026;21. https://doi.org/10.1016/j.adapen.2025.100258.

[33] Thonemann N, Schulte A, Maga D. How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. Sustainability 2020;12(3). https://doi.org/10.3390/su12031192.

[34] Kanchiralla FM, Brynolf S, Mjelde A. Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations. Energy Environ Sci 2024. https://doi.org/10.1039/D4EE01641F. 10.1039/D4EE01641F.

[35] Kanchiralla FM, Brynolf S, Malmgren E, Hansson J, Grahn M. Life-cycle assessment and costing of fuels and propulsion systems in future fossil-free shipping. Environ Sci Technol Sep 6 2022;56(17):12517–31. https://doi.org/10.1021/acs.est.2c03016.

[36] Antonini C, Treyer K, Moioli E, Bauer C, Schildhauer TJ, Mazzotti M. Hydrogen from wood gasification with CCS – a techno-environmental analysis of production and use as transport fuel. Sustain Energy Fuels 2021;5(10):2602–21. https://doi.org/10.1039/d0se01637c.

[37] Sacchi R, et al. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew Sustain Energy Rev 2022;160. https://doi.org/10.1016/j.rser.2022.112311.

[38] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21(9):1218–30. https://doi.org/10.1007/s11367-016-1087-8.

[39] Stehfest E, van Vuuren D, Bouwman L, Kram T. Integrated assessment of global environmental change with image 3.0: model description and policy applications. Netherlands Environmental Assessment Agency (PBL); 2014.

[40] Zampori L, rana P. Suggestions for updating the product environmental footprint (PEF) method, eur 29682 en. Luxembourg; 2019.

[41] Sala Serenella, Crenna Eleonora, Secchi Michela, Pant R. Global normalisation factors for the environmental footprint and life cycle assessment. European Commission, Joint Research Centre; 2017. ISBN 978-92-79-77213-9.

[42] IPCC. Assessment report 6: climate change 2022: mitigation of climate change. 2022.

[43] Li Y, Zhu F, Li L, Ouyang M. Electrifying heavy-duty truck through battery swapping. Joule 2024;8(6):1556–61. https://doi.org/10.1016/j.joule.2024.04.008.

[44] Cullen DA, et al. New roads and challenges for fuel cells in heavy-duty transportation. Nat Energy 2021;6(5):462–74. https://doi.org/10.1038/s41560-021-00775-z.

[45] Helgeson B, Peter J. The role of electricity in decarbonizing European road transport – Development and assessment of an integrated multi-sectoral model. Appl Energy 2020;262. https://doi.org/10.1016/j.apenergy.2019.114365.

[46] Vedhanarayanan B, Seetha Lakshmi KC. Beyond lithium-ion: emerging frontiers in next-generation battery technologies. Front Batter Electrochem 2024;3. https://doi.org/10.3389/fbael.2024.1377192.

[47] Millinger M, Hedenus F, Zeyen E, Neumann F, Reichenberg L, Berndes G. Diversity of biomass usage pathways to achieve emissions targets in the European energy system. Nature Energy 2025. https://doi.org/10.1038/s41560-024-01693-6.

[48] Costa M, Piazzullo D, Di Battista D, De Vita A. Sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant based on biomass gasification: biomass supply chain management and life cycle assessment. J Environ Manage 2022;317:115434. https://doi.org/10.1016/j.jenvman.2022.115434.

[49] Muratori M, et al. EMF-33 insights on bioenergy with carbon capture and storage (BECCS). Clim Change 2020;163(3):1621–37. https://doi.org/10.1007/s10584-020-02784-5.

[50] Marmiroli B, Venditti M, Dotelli G, Spessa E. The transport of goods in the urban environment: a comparative life cycle assessment of electric, compressed natural gas and diesel light-duty vehicles. Appl Energy 2020;260. https://doi.org/10.1016/j.apenergy.2019.114236.

[51] Zhang R, Fujimori S. The role of transport electrification in global climate change mitigation scenarios. Environ Res Lett 2020;15(3). https://doi.org/10.1088/1748-9326/ab6658.

[52] McCollum DL, et al. Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles. Nat Energy 2018;3(8):664–73. https://doi.org/10.1038/s41560-018-0195-z.

[53] Ueckerdt F, Bauer C, Dirnaichner A, Everall J, Sacchi R, Luderer G. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat Clim Chang 2021;11(5):384–93. https://doi.org/10.1038/s41558-021-01032-7.

[54] Document 32023L0959, directive (EU) 2023/959 of the european parliament and of the council of 10 may 2023 amending directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the union and decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the union greenhouse gas emission trading system (Text with eea relevance). 2023 [Online] Available: ELI, http://data.europa.eu/eli/dir/2023/959/oj.

[55] Sterner T, Coria J. Policy instruments for environmental and natural resource management. 2nd ed. New York, London: RFF Press; 2012.

[56] Document 32023R1804, regulation (EU) 2023/1804 of the european parliament and of the council of13 september 2023on the deployment of alternative fuels infrastructure, and repealing directive 2014/94/EU (Text with eea relevance). ELI; 2023 [Online] Available, http://data.europa.eu/eli/reg/2023/1804/oj.

[57] Ager-Wick Ellingsen L, Thorne RJayne, Wind J, Figenbaum E, Romare M, Nordelöf A. Life cycle assessment of battery electric buses. Transp Res Part D: Transport Environ 2022;112. https://doi.org/10.1016/j.trd.2022.103498.

[58] Usai L, Hung CR, Vásquez F, Windsheimer M, Burheim OS, Strømman AH. Life cycle assessment of fuel cell systems for light duty vehicles, current state-of-the-art and future impacts. J Clean Prod 2021;280:125086. https://doi.org/10.1016/j.jclepro.2020.125086.

[59] Lotrič A, Sekavčnik M, Kuštrin I, Mori M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. Int J Hydrogen Energy 2021;46(16):10143–60. https://doi.org/10.1016/j.ijhydene.2020.06.190.

[60] Khan MHA, et al. Strategies for life cycle impact reduction of green hydrogen production – Influence of electrolyser value chain design. Int J Hydrogen Energy 2024;62:769–82. https://doi.org/10.1016/j.ijhydene.2024.01.081.