Near-term decarbonization of Class-8 heavy-duty trucks in China requires a broad mix of advanced powertrains to be complemented by low-carbon energies

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Summary

China’s climate change targets require drastic cuts in greenhouse gas (GHG) emissions from its heavy-freight logistics, but decarbonizing Class-8 heavy-duty trucks (HDT) is complicated by current limitations in alternative technologies that deter complete substitution of conventional trucks. We address existing research gaps by modelling the GHG mitigation potentials of three emerging powertrains powered by different energy sources based on the projections for China in 2030, and incorporating likely technological breakthroughs within this timeframe, to inform discussions on near-term decarbonization prospects. Here we show that there is no simple solution for the HDT sector in China where near-term technological limitations may necessitate a more targeted deployment. All three powertrains could exceed 38% GHG reductions, and potentially attaining more than 70% reduction when used in combination with low-carbon renewable energies. Achieving near-zero heavy-duty trucking requires a broader policy approach to stimulate technology developments, promote optimization of freight logistics, and incentivize behavioral changes.

Keywords

Life cycle assessment (LCA), heavy-duty truck, China, net zero, greenhouse gases (GHG), climate change, battery electric, fuel cell, hydrogen, low carbon fuel

Introduction

The transport sector emits 8.2 Gt of CO\textsubscript{2} in 2018, accounting for 24% of combustion-related CO\textsubscript{2} worldwide \textsuperscript{1}. Although the growth in greenhouse gas (GHG) emissions from transport has slowed
down, recording about 1.9% annual growth since the year 2000, the emissions from trucks and busses have recorded a higher growth rate of 2.6% annually during the same period\(^1\). Despite having a smaller vehicle stock than light-commercial vehicles, heavy-duty trucks (HDT) account for a disproportionate share of emissions\(^2\) given their larger emissions per vehicle-km and higher annual usage\(^3\). Globally, HDTs are responsible for about 70% of road freight activities and about 50% of truck energy use\(^3\). In 2018, HDTs were responsible for 1.2 Gt of CO\(_2\)\(^1\), almost 15% of total transport emissions, and by 2040 the emissions from trucks are projected to increase by another 0.6 Gt\(^4\). The rise in emissions is mainly driven by the increase in freight activities, which is expected to grow by 120% by 2050\(^4\). Demand for logistics is rising unevenly worldwide, pivoting towards Asia as the economies in this part of the world industrialize and GDPs expand\(^3\). China has the largest truck fleet in the world, with more than 10 million heavy freight trucks on the road, while the U.S. and Europe registering 7.8 million and 7.1 million respectively\(^5\). In 2018, it was estimated that the total truck distance travelled in China is about 6.5 trillion tonne-km, which is 2-3 times higher than that in the U.S. and Europe, and it is projected to double by early 2030\(^6\).

As the largest CO\(_2\) emitter in the world, responsible for about 29% of total worldwide emissions, China has pledged to peak its emissions by 2030, reducing its CO\(_2\) emissions per unit GDP by 60-65% relative to 2005 emissions, and ultimately achieve net zero emissions by 2060\(^7\),\(^8\). Thus, reducing CO\(_2\) emissions from the HDT sector in China is imperative to achieve its national climate change commitments, and to realize the global mitigation targets envisioned by the Paris Agreement. However, GHG emission from HDT is particularly hard to mitigate\(^3\),\(^6\). The sector is energy-intensive and cost-sensitive. Compared to light-duty applications, HDTs demand a much higher power to haul heavier payloads, and they typically cover much longer distances\(^9\),\(^10\). Any substitute, therefore, has to offer comparable range, power, payload, and durability. Unlike passenger cars, electrification of heavy freight logistics is generally considered to have limited feasibility with the current battery technology given that its low gravimetric energy density could incur significant penalty on the truck’s payload rating and range\(^11\)-\(^13\). Furthermore, commercial HDTs often involve long haul distances, which means the industry requires refueling infrastructures to be widely available along major logistical corridors\(^14\). This is especially relevant for Class-8 HDTs with a gross vehicle weight (GVW) greater than 30 tonne, which is typically operated almost all year round, often covering about 100,000 km per annum\(^3\).

The complexity of freight logistics is further compounded by the diverse nature of its duty-cycles, making it challenging for a single technology to offer a universal solution that meets the global trucking needs\(^15\). A broad mix of powertrain technologies and energy solutions\(^5\) are being developed as a means to mitigate the climate change impacts of this sector\(^3\). These include HDTs that are powered by highly-efficient combustion engines, battery-electric, hydrogen fuel cells, and novel low-carbon fuels. Earlier studies have focused on key parameters to improve the prospect of electrifying the HDT sector\(^12\),\(^13\), opportunities to electrify selected duty-cycles\(^16\),\(^17\), the potential for emerging technologies to improve the feasibility of electric trucks\(^18\),\(^19\), and the significant strain on lithium supply worldwide with the additional demand for batteries from the HDT segment\(^20\). Multiple studies have reported the GHG impacts of alternative powertrains such
as electric and fuel cell trucks, including at the overall fleet level in China, to support the development of near and long-term approaches to decarbonize China’s HDT sector through 2050. Many of these studies offer useful technology insights that are generalizable worldwide. However, there are country-specific characteristics that can influence the overall findings substantially, including the current and projected national energy mix, and the HDT truck classification in China that are distinct from other countries. While there are reports that have focused on the HDT sector in China, oftentimes they adopt assumptions that are dissimilar to each other making direct comparison between studies challenging. Importantly, we are not aware of any comprehensive study that has conducted a comparative assessment covering a broad range of technological options that include advanced combustion trucks powered by low-carbon synthetic fuel alongside other emerging alternatives. There is a growing literature on the potential for novel low-carbon fuel to decarbonize the hard-to-abate sectors, which can be a key mitigation option considering that combustion-based engines are still expected to power a significant share of the HDT sector in the near-term. Thus, it is critical that any comparative assessment include a wide array of technologies, incorporating likely technology breakthroughs within the timeframe, and adopt similar underlying assumptions to inform the discussions on near-term decarbonization pathways for the HDT segment in China.

Here we model the life cycle GHG emissions of HDTs in China in 2030. We compare the climate change mitigation potential of three advanced powertrain technologies (highly-efficient combustion truck, battery-electric truck, and fuel-cell truck) powered by different conventional and low-carbon energy sources based on the projected energy mix for China in 2030. The life cycle assessment (LCA) incorporates emissions from the energy life cycle (i.e. conventional diesel, low-carbon fuels, electricity, and hydrogen productions), vehicle manufacturing (including battery productions and end-of-life (EOL) recycling), and vehicle use-phase. We examine the trade-offs between haulage distances, energy density and the total truck payload. We quantify the CO2 reduction potential of the different energy-powertrain combinations and contrast them against a traditional Class-8 HDT in China in 2016. We found that all three powertrain types could enable more than 38% reduction in life cycle GHG emissions and with the prospects of achieving up to 80% reduction when used in combination with low-carbon energy sources. Given the limitation in battery density, an electric truck could experience as much as 7-58% penalty in the maximum payload tonnage depending on the desired all-electric range and the permissible GVW limit. However, accelerating the deployment of ultra-fast, high-power charging networks could significantly reduce the charging duration by 57-85%, potentially alleviating the pressure on batteries by enabling smaller battery packs and a more frequent fast-charge. China is currently leading the way when it comes to the use of hydrogen for commercial heavy-duty applications. Given the diversity of hydrogen production and supply in China, the GHG reduction prospect can vary from more than 80% reduction to an increase in emission by 57% compared to the HDT baseline in 2016. There is no technology silver-bullet within the HDT sector in China, therefore, we outline the opportunities and limitations for each technology, stressing the importance of LCA-based policies to guide the industry towards a net-zero emissions future. We conclude that
the decarbonization of the HDT sector requires a broader policy approach to stimulate technology development and deployment, promote logistical system re-design and optimization, and incentivize changes in behaviors amongst consumers, drivers, and freight operators.

Results

Method Summary

We focus on a Class-8 HDT with gross vehicle weight (GVW) range of 27-36 tonne since it is integral to many economic activities, while climate change mitigation within this vehicle class is known to be particularly difficult\textsuperscript{5}. Furthermore, there are more data widely available on emerging technologies applicable to vehicles within this GVW range based on engineering advances that have been made publicly available, for example, by the U.S. Department of Energy (DOE) under their SuperTruck and hydrogen fuel cell truck programs. Within the Chinese context, a Class-8 truck in this study is equivalent to an N3 tractor-trailer segment, which exhibited the largest growth in market share between 2012 and 2017, with sales tripling and exceeding 500,000 units in 2017\textsuperscript{29}.

Vehicle segmentation in China is complex, and the applicable standard covers a broad GVW range. Unlike many other countries, the legal maximum GVW can reach 49 tonne for a 6x4 driveline configuration\textsuperscript{30}. However, from 2017 to 2019, more than 90\% of the electric trucks sold in China had a GVW of 3.5-5 tonne, with only 2.2\% sold within the 16-32 tonne GVW segment\textsuperscript{31}. This reflects the challenges of developing and commercializing an alternative powertrain solution for heavier trucks. As far as we are aware, none of the recent announcements by major manufacturers of heavy-duty fuel cell and electric trucks have targeted vehicles above the 36 tonne GVW category\textsuperscript{32}. Therefore, given the 2030 timeline of this study, we narrow our focus on the 27-36 tonne GVW segment as the base case, with sensitivity analysis on GVW up to 49 tonne.

The average curb-weight for a tractor and trailer in China is about 9 tonne and 7 tonne respectively, resulting in an average gross unloaded weight of 16 tonne in 2017\textsuperscript{29, 30}. A typical tractor-trailer in China is driven on the expressway 90\% of the time and at an average speed of 60 km/h\textsuperscript{30}.

We assessed three advanced powertrain technologies in combination with various energy sources (Table S1): (1) a high-efficiency combustion-based truck (HET), modelled after Phase 2 of the U.S. SuperTruck program and fueled by conventional diesel fuels; (2) a highly-efficient truck (HET) fueled by low-carbon synthetic fuels (LCF) derived from direct air capture (DAC) of CO\textsubscript{2}; (3) an electric truck (BET) based on emerging battery technology and powered by the average electric grid projected for China in 2030; and (4) a hydrogen fuel-cell truck (FCT) using a range of hydrogen mixes in China, including green and grey hydrogens produced from a variety of pathways based on the projections by the China Hydrogen Alliance\textsuperscript{33}.

Details of the modelling techniques are provided in the section on Experimental Procedures (Equation 1). Briefly, we adopted a bottom-up engineering approach to estimate the truck energy demand by utilizing a standard vehicle dynamic model (Equation 2 in Experimental Procedures)
to quantify the energy required to overcome the aerodynamic drag, frictional force, road gradient, and inertial resistance over a specified distance given its powertrain efficiency. We assessed haulage distances of 150, 300, 600, and 900 miles (i.e., 240, 480, 960, and 1440 km respectively). Based on the gravimetric energy density of the energy sources and the total truck weight limit, we estimated the maximum payload tonnage of the tractor-trailer (Equation 3 in Experimental Procedures). The life cycle GHG emission calculations consider the projected energy mixes in China for 2030 (Table 1 and Table 2), and the vehicle manufacturing and recycling emissions, including those associated with the battery-electric and fuel-cell powertrains.

### Table 1 Power generation mixes in China in 2030 based on the IEA’s projection².

<table>
<thead>
<tr>
<th>Electricity generation sources</th>
<th>Stated Policy Scenario</th>
<th>Current Policy Scenario</th>
<th>Sustainable Development Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>51%</td>
<td>52%</td>
<td>38%</td>
</tr>
<tr>
<td>Oil</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>7%</td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6%</td>
<td>6%</td>
<td>8%</td>
</tr>
<tr>
<td>Renewables</td>
<td>36%</td>
<td>34%</td>
<td>47%</td>
</tr>
<tr>
<td>Hydro</td>
<td>14%</td>
<td>14%</td>
<td>16%</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>3%</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Wind</td>
<td>10%</td>
<td>9%</td>
<td>13%</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Solar PV</td>
<td>10%</td>
<td>9%</td>
<td>14%</td>
</tr>
<tr>
<td>CSP</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Marine</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

### Table 2 Hydrogen production scenarios based on the China Hydrogen Alliance³³.

<table>
<thead>
<tr>
<th>China hydrogen supplies in 2030</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal gasification</td>
<td>60%</td>
<td>45%</td>
<td>0%</td>
</tr>
<tr>
<td>Steam methane reforming (SMR)</td>
<td>0</td>
<td>15%</td>
<td>60%</td>
</tr>
<tr>
<td>By product of chlor-alkali</td>
<td>0</td>
<td>13%</td>
<td>23%</td>
</tr>
<tr>
<td>By product of coke oven gas</td>
<td>23%</td>
<td>10%</td>
<td>0</td>
</tr>
<tr>
<td>Alkaline water electrolysis - Wind power</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Biomass to H2</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>

There is no technology silver-bullet

Reducing CO₂ emissions from HDTs in China by 2030 requires the use of both, advanced powertrain technologies and fuels with lower climate change impacts (Figure 1). All three powertrain types could enable more than 40% CO₂ reduction when powered by low-carbon energy sources; on the other hand, the use of CO₂-intensive fuels resulted in a worse overall
emission than the 2016 baseline. Thus, it brings into focus the importance of considering the overall life cycle emissions of the sector, including the accessibility to clean energy sources, when prioritizing technologies for climate change mitigation.

Improving the efficiency of combustion trucks resulted in 38% reduction in overall emissions, and when powered by low-carbon fuels, the CO\(_2\) reduction is as high as 78%. For an electric truck equipped with 260kWh battery, with an all-electric range of about 240km, the CO\(_2\) reduction depends critically on the projected grid mix by 2030: 25% reduction under the IEA’s Stated Policy Scenario (SPS), and 39% reduction under the more ambitious Sustainable Development Scenario (SDS). However, a BET has a larger GHG reduction prospect with deeper decarbonization of the power sector.

Meanwhile hydrogen can be supplied from multiple sources in China: conventional hydrogens are produced via coal gasification, steam methane reforming, and as byproducts from several industrial processes like coke oven gas and chlor-alkali. On the other hand, green hydrogens are produced from biomass or electrolysis using renewable electricity. The CO\(_2\) impacts of hydrogen fuel cell trucks range from 83% reduction to 57% worse than the HDT baseline in 2016, depending on the manufacturing and supply of the hydrogen. By 2030, the national hydrogen mix is likely to be from multiple sources with provincial preferences based on the availability and accessibility to the lowest cost hydrogen supply within the region. The China Hydrogen Alliance developed three different supply scenarios (Table 2), which resulted in CO\(_2\) reductions of -12% (worse), 6% and 46% for scenario 1, 2 and 3 respectively. Just as important, the distribution of hydrogen can be energy intensive particularly when it is transported using trailers. Thus, long distance hydrogen distributions within China requires the construction of pipeline networks, without which the use of trailers is feasible for a more localized distribution.

**Long-haul freight and payload implications**

The range expectations for a Class-8 HDT in China varies significantly between fleet operations and vehicle age\(^3,6,34\). This is less problematic for diesel trucks and hydrogen fuel cell trucks with their respective gravimetric energy densities that are 45 and 120 times \(^{11}\) higher compared to even the most advanced and futuristic lithium-batteries. To offer comparable range, a battery truck will need to be equipped with a larger and heavier battery pack, and therefore its maximum payload is reduced by 7-58% (Figure 2(A)).

However, increasing the legal GVW allowance of the truck could partly compensate for the loss in maximum payload as a result of using larger batteries. The tractor-trailer in China can reach a maximum GVW of 49 tonne, which is heavier than the U.S. and Europe with a maximum GVW allowance of 36 tonne\(^{35}\) and 40 tonne\(^{36}\) respectively. For an electric truck with a 300 miles range, the payload penalty drops from 17% to 12% relative to a comparable diesel truck when the GVW limit is raised from 27 tonne to 49 tonne (Figure 2(B)). However, raising the permissible GVW limit will need to consider the safety aspects of the overall logistics operations and its compatibility with existing road infrastructures in the market.
Furthermore, lithium batteries are generally more CO$_2$ intensive to produce. Thus, with lower maximum payload and higher battery production emissions, increasing the all-electric range of a BET will negatively impact its overall emissions on a per tonne-km basis (Figures 2(C) and 2(D)). This would preclude the use of electric truck in long-distance haulage, particularly beyond 500 km range (or about 300 miles). Therefore, energy-dense fuels are likely the preferred energy-source for long-distance heavy-duty freight activities$^{11,37}$. This includes hydrogen fuels and liquid hydrocarbons, both of which can enable near-zero emissions if produced under the right conditions (Figure S1).

**The various shades of hydrogen**

However, the choice of hydrogen is particularly key to drive FCT emissions closer towards zero. In 2016, most of the hydrogens produced in China are grey hydrogen, either via coal gasification, steam methane reforming (SMR) or by-products of chlor-alkali and coke-oven gas industries, with respective market shares of 62%, 19%, 9% and 9%$^{38,39}$. Pivoting towards lower carbon hydrogen sources could reduce the overall emissions of FCT significantly (Figure 1): in the best case, when the hydrogen is produced via electrolysis, the overall CO$_2$ emissions is reduced by 83% relative to an HDT in 2016. However, it is vital that the electrolysis process utilizes cleaner electricity like wind power, and not the average electric grid in China. In 2030, coal is still expected to account for more than 50% of power generation, and therefore FCTs running on hydrogen produced via grid-powered electrolysis would result in 57% higher emissions than the 2016 HDT baseline. The byproduct hydrogen from the chlor-alkali industrial process is considered a low-carbon hydrogen$^{40}$ given that it carries a lower emissions burden; hydrogen is a byproduct of the industry (mass share of 1.3%) whose primary purpose is to produce chlorine and caustic soda. It offers a promising low-cost hydrogen source$^{40}$, however, since it is a mature industry, there is limited scale-up opportunity. Today the chlor-alkali industry in China is centered in the eastern provinces of Shandong and Jiangsu$^{38}$, and therefore it presents a niche opportunity to the surrounding areas.

**How electric trucks are charged**

The CO$_2$ reduction potential of an electric truck depends critically on breakthroughs in battery technology. Maximizing payload is key to overall freight efficiency, however the maximum gross vehicle weight is often limited by regulations due to safety considerations. Thus, higher battery energy density could ease the trade-off between haulage distance and total freight tonnage. Alternatively, accelerating the development of ultra-fast, high-power charging networks could alleviate the pressure on batteries by enabling smaller battery packs. With shorter all-electric range and more frequent fast-charging, the truck no longer needs a large and heavy battery$^{19}$. Today, most battery electric passenger cars can fast-charge with a 150kW charger$^{41}$, with up to 350 kW fast-chargers already available$^{41-44}$. For a battery-electric heavy-duty truck to mimic the charging pattern of an electric car, or come close to being comparable to a regular diesel truck, a high-power fast-charger in the order of 1MW is required$^{19}$. The availability of ultra-fast, high-power charging infrastructure can reduce the charging duration substantially, between 57% and
85% (Figure 3), from more than 6-hours charging time (i.e., charging a 1100 kWh battery using a 150kW charger) to less than an hour (i.e., when charged using a 1MW charger). While a MW-level fast-charger is not yet available, various R&D efforts are currently ongoing\textsuperscript{45}; however, its deployment could be complicated by other factors including the limitations in the local power grid. Another important enabler for BET is the accessibility to clean power sources, which involves two key elements: the capacity to generate sufficient quantities of low carbon electricity, and the ability to provide adequate infrastructures along major trucking corridors.

**Measurements of freight efficiency**

Despite the payload implication, an all-electric truck is still a highly efficient powertrain given the minimal energy conversions involved. On a vehicle level, an electric truck would still deliver the highest freight efficiency when measured on a tonne-km per liter of diesel-equivalent basis (Figure S2(A)): a longer all-electric range truck would incur a payload penalty, and correspondingly the freight efficiency would decrease. However, when the truck efficiency is measured on a lifecycle basis, taking into consideration of the energy consumptions and loses from well-to-wheels (WTW), the total energy consumed per tonne-km shows a different picture with no obvious trend (Figure S2(B)). This is because the energy mix in China in 2030, whether for electricity generation or hydrogen production, will still be heavily dependent on non-renewable pathways. Therefore, the multi-step energy transformations in the alternative energy and powertrain combinations result in a lower overall energy efficiency (Figure S2(C)) for scenarios where renewables are not yet the dominant source of energy.

The lifecycle energy efficiencies of a battery-electric and fuel cell trucks reflect the likely energy mix in China by 2030 (Figure S2(C)). A more aggressive decarbonization rate can change this picture dramatically, especially for a battery-electric truck (Figure 4). As an example, when the electricity is generated entirely from wind, the overall lifecycle efficiency of the electric-truck can be as high as 77%. However, this is not the case for hydrogen fuel-cell trucks. Producing hydrogen via alkaline electrolysis, using wind-generated electricity, is less efficient compared to other conventional pathways like steam-methane reforming and coal gasification\textsuperscript{46}.

**Sharpening the arrows in the quiver**

Ultimately, to achieve these CO\textsubscript{2} reductions by 2030, several important technological hurdles have to be overcome. While concomitant improvements in vehicle designs to reduce the aerodynamic drag, rolling resistance of the tyres and weight reduction through vehicle light weighting can provide CO\textsubscript{2} reduction benefits in all powertrain types, there are also unique opportunities for each (Figure S3).

For the combustion engine trucks, the two biggest opportunities are improvements in engine efficiency, and the use of low-carbon fuels (Figure 5). Several truck efficiency initiatives are ongoing worldwide targeting to raise the efficiency of heavy-duty engines from the current average of 44% to about 55%. This includes the SuperTruck-II program in the U.S.\textsuperscript{47}, and similar government-backed initiatives in Europe and China\textsuperscript{48}. Achieving 55% break thermal efficiency
(BTE) will be a significant milestone, but not an impossible target by 2030, as several manufacturers have already successfully demonstrated engines with a BTE of more than 51%\textsuperscript{49-52}. On the other hand, while low carbon synthetic fuel presents significant opportunity, it will require important technical and policy considerations. Synthetic electro-fuels derived from captured CO\textsubscript{2} are only low carbon if the production process utilizes low carbon energy sources\textsuperscript{11}. Prior studies have shown that the carbon intensity of the electricity used in the production of a synthetic fuel must be well below 150 gCO\textsubscript{2eq}/kWh for it to be considered a low carbon fuel (Figure S4 and Table S2)\textsuperscript{26, 27}. This should preclude usage of the average grid electricity in China since it is not expected to be sufficiently decarbonized by 2030, in which its projected carbon intensity is at least 4 times above the upper limit requirement of a low-carbon synthetic fuel. Without decarbonized electricity sources, the GHG reduction potential of a synthetic electro-fuel is severely diminished (Figure 5(A) and Figure 5(B)). Therefore, this underscores the importance of locating the production facilities in geographical regions with an abundance of renewable electricity generation capacities. Just as important, the scale-up and commercialization of low carbon synthetic fuels require strong government signals. Without policy certainty, it is unlikely to attract the necessary investments to turn this into a reality. As of today, it does not seem probable that a low-carbon synthetic electro-fuel will be available in China in sufficient quantities by 2030. It is more likely to be used as a blending component in diesel in increasing concentrations, thereby gradually reducing the carbon intensity of the blended fuel over time (Figure 5(B)).

Power generation and supply is central to an electric truck, therefore, diversity in charging characteristics can have a large effect on its GHG reduction potential. The use of China’s average grid mixes in 2030, due to data limitations, fails to capture the regional heterogeneity\textsuperscript{9} in power generation profiles across the 31 provinces in China. In 2018, its carbon intensity has been reported to vary substantially by -74% to +31% around the nationwide average of 680 gCO\textsubscript{2eq}/kWh\textsuperscript{53}. Moreover, with higher penetration of renewable electricity generations, there will be larger diurnal and seasonal fluctuations due to the intermittency of wind and solar, resulting in a nonuniform emission intensity throughout the day and year\textsuperscript{54}. Furthermore, simultaneous electric vehicle charging during high load period may lead to higher peak demand, leading to the utilization of residual or marginal electricity sources that are typically inefficient and more emissions intensive to generate than the national average\textsuperscript{21, 55-57}. Therefore, the region and time-of-day when the electric trucks are charged will affect its overall life cycle GHG emissions. However, projecting the geographical diversity and temporal variability of the electricity mixes in 2030, and by individual provinces in China, is challenging. Figure 6 demonstrates the impact of the grid carbon intensity on the overall life cycle GHG emission of electric trucks with varying battery sizes and all-electric ranges. This shows that any significant departure from the IEA’s SPS forecast for China in 2030, either due to the use of marginal electricity or as a result of other variabilities, may lead to a different conclusion.

For hydrogen FCTs, it is of great importance that the hydrogen is produced via low carbon pathways. This can include hydrogen byproducts obtained from the chlor-alkali process, blue
hydrogen, for example by combining SMR with a carbon capture system, and green hydrogen, which utilizes renewable electricity to power the electrolysis process. There is a large prospect for the use of hydrogen to decarbonize the commercial heavy-duty truck sector, in which China is currently leading the way. In 2020, there are more than 8400 fuel cell vehicles on the road and about 85 refueling stations in China\textsuperscript{58}. China targets to grow its fuel cell vehicle fleet to 1.2 million and 11 million by 2035 and 2060 respectively, comprising mainly commercial vehicles, while also aiming for 10,000 hydrogen refueling stations by 2035\textsuperscript{33}. Given the diversity in the hydrogen supply sources available in China, the GHG reduction potential of a hydrogen fuel cell truck is highly uncertain as demonstrated in this study (Figure 1). This has led the China Hydrogen Alliance to develop a life cycle GHG standard to establish three different hydrogen categories, those are “low carbon hydrogen”, “clean hydrogen”, and “renewable hydrogen”, with life cycle GHG thresholds of 14.51 kgCO$_{2eq}$/kg-$H_2$, 4.9 kgCO$_{2eq}$/kg-$H_2$, and 4.9 kgCO$_{2eq}$/kg-$H_2$ respectively, but with the additional requirement that a renewable hydrogen has to be derived from renewable sources\textsuperscript{59, 60}. Achieving these GHG thresholds for hydrogen would result in the fuel cell truck to emit about 41\% and 78\% lower GHGs than a conventional diesel truck in 2016 (Figure 7). The adoption of a life cycle GHG standard for hydrogen has the potential to drive emissions lower, irrespective of the hydrogen sources, therefore opening up a much larger technological possibility for decarbonizing the hard-to-abate sectors including commercial heavy-duty transport.

Relatedly, the global freight transition will be influenced by the availability and accessibility to raw critical metals: lithium, cobalt, nickel, and graphite are critical metals typically used in a battery for an electric truck, while platinum, palladium, and rhodium are critical metals for a hydrogen fuel cell. Clean energy technologies, such as battery storage, wind turbines, solar panels, and fuel cells demand more of these precious metals, which will be in competition with a wide array of existing applications, including consumer electronics. Recent analysis suggests that the global lithium resources will not be able to sustain simultaneous electrification of light-duty and heavy-duty road vehicles\textsuperscript{20}; thus, mass electrification of the HDT segment would come at a significant risk. Today, productions of critical metals are geographically concentrated where two mining countries accounted for 70\% of each\textsuperscript{61}, lithium (Chile and Australia), cobalt (DR Congo and Australia), and graphite (China and Brazil) supplies worldwide, exposing the vulnerability in the supply chains globally. Concerns have been raised that the growing demand for these critical materials could exert significant environmental and social pressures particularly in producing countries and potentially leading to unsustainable mining practices\textsuperscript{62}. There have been calls for better global governance of the world’s critical resources \textsuperscript{63} to ensure that they are produced sustainably and consumed optimally. While terrestrial mining will likely dominate global supplies for some time to come, there are growing pressures to allow oceanic mining to alleviate the supply constraints worldwide\textsuperscript{64}. However, regulatory decisions must be informed by science to ensure environmental safeguards to negate the risk of accidental damage to the fragile ecosystem of the deep-seas\textsuperscript{65}. Ultimately, this underscores the need for a holistic decarbonization strategy that considers the trade-offs between technologies and their
environmental aspects-impacts to ensure effective GHG mitigation approaches with manageable unintended consequences.

**Hauling towards zero**

Currently there isn’t a technology silver-bullet that has been proven to be cost-effective and reliable universally. With the right combination of fuels and powertrains, substantial reduction in emissions can be achieved by the different technologies, bringing emissions closer towards zero. Therefore, in this case, the choice of technology is only relevant insofar as how effectively it can be deployed considering the fleet dynamics, the availability of necessary infrastructures, and the cost-effectiveness of the utility that it is expected to provide. Thus, a mix of fuels and powertrain technologies will likely serve the diverse needs of the sector based on the technological viability for the different duty cycles\textsuperscript{13, 16, 17, 66}: electric trucks for shorter haulages, hydrogen fuel cell trucks for long-haul distances along major hydrogen-supply corridors, and efficient combustion trucks for wider freight distributions. Targeted deployments of transition technologies have to be guided by the availability of low carbon energy sources that are measured on a life cycle basis to ensure overall reduction in emissions, and to avoid any unintended leakages in emissions from the transport sector to a different industry.

Alternative energies and powertrains have zero tailpipe emissions, which imply a shift in GHG emissions from road transport to other sectors and jurisdictions, including power generation and vehicle manufacturing. Importantly, today, transport regulations globally, whether fuel economy or GHG emission standards, focus on the vehicle use-phase, and not on the entire energy/vehicle life cycle\textsuperscript{67}. Therefore, existing standards have to be strengthened to close potential loopholes that may lead to emissions leakages across jurisdictions or sectors. Revealingly, a recent analysis by the U.S. Argonne National Laboratory estimated that, for light duty road vehicles sold within the 2012-2025 timeframe, more than 1 billion tonnes of cumulative unaccounted CO\textsubscript{2eq} are due to loopholes in existing regulations in the U.S., EU, and China; the omitted upstream electricity emissions alone is responsible for over 400 million tonnes of CO\textsubscript{2eq}\textsuperscript{68}. Emissions leakages can be significant, particularly under unilateral national and sub-national GHG emission policies\textsuperscript{69-72}, including in transport-specific policies, underscoring the requirements for a complementary and coordinated strategy\textsuperscript{73-75}.

It is increasingly evident, however, that a technology-centric policy on its own is not adequate to meet the sectoral mitigation target\textsuperscript{66, 76-78}. Overall emissions of GHGs from the commercial and heavy-duty road sector can be represented by the extended Kaya identity\textsuperscript{79}. Improvements in powertrain technologies and the use of lower carbon energy sources must be complemented by a broader approach to address society’s growing consumption habits\textsuperscript{78} and any inefficiency in the global logistics and supply chains. This requires behavior-centric policies to incentivize consumers to reduce excessive consumption, and stimulate reusing, repurposing, and recycling of goods as much as possible. Collaboration within and across the industry\textsuperscript{80, 81}, as well as enhanced connectivity and data analytics could facilitate improvements in logistics through load consolidation and route, schedule, and network optimizations\textsuperscript{82, 83}. The availability of a wider rail
infrastructure and waterways network could support a modal shift towards a lower carbon freight alternative. In the longer term, the widespread use of 3-D printing could obviate the need for extensive supply chains by enabling bespoke design and printing closer to the end user thereby decentralizing supply chain nodes; however, this has to be balanced against the possible longer distance transport of raw feedstock materials.

This brings into focus the requirement for a broad policy approach to stimulate technology development and deployment, promote logistical system re-design and optimization, and incentivize changes in behaviors amongst consumers, drivers, and freight operators. However, today, an important bottleneck in decarbonizing the sector is the relatively slow diffusion of advanced truck technologies, particularly to developing countries. While the average age of the truck fleets in developed countries like the United States and the European Union tend to be about 8 years, it is much older in developing countries, even exceeding 15 years in some markets. Fleet modernization, therefore, presents an additional challenge to decarbonizing the truck sector. Advanced low-carbon powertrains often incur significantly higher upfront cost, and without subsidies or the availability of green financing schemes, fleet decarbonization will be limited by the slow vehicle turnover rate. In the absence of a truck scrappage incentive, low-carbon drop-in fuel, whether renewable bio-based fuel or CO₂-derived synthetic fuel, has to play a central role to accelerate the decarbonization of older vehicles still existing within the fleet.

Reflections on methodological limitations

Like any other modelling exercises, the strength of our analysis depends on the methodological approach and the assumptions made. The three most important simplifications include: (1) the use of an engineering-based vehicle energy demand estimation method, (2) the absence of vehicle fleet dynamics, and (3) the accuracy of technological projections. These simplifications, though we believe is necessary to avoid over-complicating the study, can have implications on the outcomes, which are briefly discussed below.

First, to estimate the truck energy demand, we utilized a bottom-up model (Equation 2 in Experimental Procedures) to quantify the energy required to overcome the aerodynamic drag, frictional force, road gradient, and inertial resistance. This is an engineering estimate based on the peak efficiency of the truck, which correlates reasonably well with steady state highway driving. Currently, an average truck in China is driven on the expressway 90% of the time with an average speed of 60km/h, therefore, we consider this to be a reasonable approximation. However, the actual on-road vehicle energy use can diverge from this engineering estimate based on several external variables including actual drive cycles, road conditions, ambient temperatures and more. The effects of these variables on the real-world energy consumption can vary between trucks and powertrain types; this is not yet fully understood for heavy-duty trucks, thus complicating efforts to build-in any real-world correction factors. For example, ambient temperature tends to have a larger effect on batteries that can worsen its total energy consumption, in which for passenger cars the penalty factor can be as high as 40%. However, unlike passenger cars, there is not enough study that has been done to develop correction factors.
for heavy-duty trucks. On the other hand, the use of empirical energy consumptions for trucks is hampered by the fact that this study evaluates advanced and futuristic powertrains emerging in the 2030 timeframe. The technologies are not yet commercially available in the market today. Given the aforementioned limitations, the engineering approach that we have adopted here allows for a fairer comparison between technologies, which is also consistent with the approaches taken in the literature. However, the deterioration of energy consumption in real-world scenario means that the absolute life cycle GHG emissions reported here can actually be worse in reality. For completeness, a comparison between the outcomes from this study and values from the literature are provided in the supporting document: Figure S5 compares the estimated fuel consumption of a diesel truck in 2016; Figure S6 provides a comparison on the estimated fuel efficiency of a diesel truck and hydrogen fuel cell truck in 2030 between this study and values in the literature; and Figure S7 compares the estimated energy consumption for an electric truck in 2030 as well as the battery requirements for the different electric ranges.

Second, this study compares the life cycle GHG emissions of energy and powertrain technologies, on a vehicle basis, by aggregating the emissions over the product lifetime. Hence, it is not designed to assess the mitigation potential on a fleet level. The effectiveness of the technology as a climate change mitigation solution is bound to the overall fleet dynamic, which depends critically on the technology adoption rate and vehicle stock turnover. Therefore, although a technology can enable 40% GHG reduction on an LCA basis, the actual realizable savings on a fleet level depends on the speed of deployment.

Third, this study is a forward-looking assessment, and therefore several assumptions about technological improvement rates were made. This include the speed of electric power decarbonization, the rate of battery density improvements, the source of hydrogen used, and more. Furthermore, this study did not evaluate the effects of tail-events such as a significant breakthrough in technology or the adoption of an improbable policy measure; for example, the development and deployment of advanced (beyond Lithium) battery technologies by 2030, or the complete ban on the use of coal in China’s energy mix by 2030. These are events with low probability, but can likely have a significant impact on the outcomes of this study.

Although this study quantified the opportunities and challenges for mitigating GHG emissions specific to China’s heavy-duty transport sector, many of the qualitative findings, particularly the discussions in the preceding sections, are generalizable to other regions. Most notably is the requirement for low-carbon energy sources regardless of the powertrain types. Achieving near-term and long-term GHG reductions, therefore, must involve extensive systems-based analysis to consider the technology’s readiness level, the availability and accessibility to low carbon energy sources in a particular region, the utility requirements of the different duty-cycles, and evaluation of potential trade-offs in policy decisions. Through careful planning and effective implementation, policies can facilitate an organized transition towards a sustainable freight industry.
Experimental Procedures

Resource availability

Lead contact

Further information and reasonable requests should be directed to the Lead Contact, Kexin Wang (kexin.wang.alice@outlook.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

All of the data sources that support the findings of this study are documented in the section on Experimental Procedures and supplemented by the Supporting Document.

Life Cycle Assessment (LCA)

We developed an excel-based life cycle assessment model for heavy-duty trucks in China comprising of three modules: vehicle energy use, fuel/energy production, and vehicle manufacturing emissions (Equation 1).

\[
LCE \left( \frac{gCO_{2eq}}{\text{ton.km}} \right) = \frac{Ep \left( \frac{kWh}{\text{km}} \right) \times CI_E \left( \frac{gCO_{2eq}}{\text{kWh}} \right)}{D \left( \frac{\text{km}}{} \right)} + \frac{VLC \left( gCO_{2eq} \right)}{WL \left( \text{ton} \right)} \times \frac{\text{Lifetime mileage (km)}}{WL \left( \text{ton} \right)}
\]

(Equation 1)

Where:

\[
LCE = \text{Life cycle GHG emissions}
\]

\[
Ep = \text{Vehicle energy requirement}
\]

\[
CI_E = \text{Carbon intensity of fuel/energy from well-to-wheels.}
\]

\[
VLC = \text{Vehicle life cycle emissions including vehicle manufacturing, battery productions and end-of-life recycling.}
\]

\[
WL = \text{Payload}
\]

\[
D = \text{Distance}
\]

Vehicle energy use (Ep): We utilized a standard vehicle dynamic model to estimate the truck pack energy required similar to the methods deployed by \cite{2,12,18,92,93}. A vehicle dynamic model is a bottom-up engineering approach, described by equation 2, which estimates the energy required...
to overcome the aerodynamic drag, frictional force, road gradient, and inertial resistance in order
to drive a truck over a specified distance given its powertrain efficiency.

$$E_p = \left[ \left( \frac{1}{2} \rho \cdot C_d \cdot A \cdot v_{rms}^3 + C_{rr} \cdot W_T \cdot g \cdot v + t_f \cdot W_T \cdot g \cdot v \cdot Z \right) \cdot \frac{1}{\eta_{fcw}} + \frac{1}{2} W_T \cdot v \cdot a \right] \cdot \left( \frac{1}{\eta_{fcw}} - \eta_{fcw} \cdot \eta_{brk} \right) \cdot \frac{D}{v}$$

(Equation 2)

Where:

- $E_p$ = energy utilized to overcome aerodynamic drag forces, frictional forces, the road
- $Cd$ = coefficient of drag
- $v$ = average velocity
- $v_{rms}$ = root-mean-square of the velocity
- $Crr$ = coefficient of rolling resistance
- $Z$ = road gradient
- $D$ = driving distance/range
- $t_f$ = fraction of time the vehicle spends at a road grade
- $\rho$ = density of air
- $g$ = acceleration of gravity
- $A$ = frontal area of the vehicle
- $a$ = mean acceleration or deceleration of the vehicle
- $\eta_{fcw}$ = fuel cell-to-wheels efficiency ($\eta_{bw}$: battery-to-wheels efficiency; $\eta_{ew}$: engine-to-wheels efficiency)
- $\eta_{brk}$ = efficiency of the brakes

Combustion-engine truck. For the year 2030, we adopted the Class-8 heavy-duty truck efficiency
target by the U.S. Department of Energy's (DOE) Vehicle Technologies Office (VTO) SuperTruck-II
program. The U.S. SuperTruck-II program that was initiated in 2016\textsuperscript{47} aims to double freight
efficiency (on a tonne-mile-per-gallon basis) and develop cost-effective efficiency technologies
to demonstrate a minimum 55% engine break thermal efficiency (BTE) at 104km/h on a
dynamometer, by 2021\textsuperscript{94}. This is also consistent with development activities happening in parallel
funded by the European governments\textsuperscript{48}. Based on the 2020 Annual Merit Review by the U.S.
DOE’s VTO, several truck manufacturers, including Daimler\textsuperscript{51}, Volvo\textsuperscript{49}, Cummins/Peterbilt\textsuperscript{50}, and
PACCAR\textsuperscript{95} are on track to achieving the efficiency targets. Most project teams have already
demonstrated more than 51% BTE, which represents a significant increase from the 46% BTE
baseline. In 2020, the leading Chinese diesel engine manufacturer, WeiChai, jointly with Bosch,
successfully achieved 50.3% BTE\textsuperscript{52}. Important strategies for achieving the targets include
combustion optimizations, reductions in frictional and parasitic losses, improved air handling,
and the use of waste heat recovery techniques. Such improvements are expected to be achievable by 2025 and made commercial by 2030.

**Battery-electric truck.** Two key parameters for the battery-electric truck is the battery-to-wheels efficiency, and the gravimetric energy density of the battery. The battery-to-wheels efficiency for an electric powertrain is already quite high, and in 2030 we assumed it to be 85%. There is a variety of battery technologies deployed in the market today, with differences between countries and transport sectors. Although significant progress has been made in recent years, there is still a large degree of uncertainty over its future outlook. Today the battery density in China averages around 200 Wh/kg\(^96\), and for the year 2030, we adopted a distribution range between 200 and 400 Wh/kg, with a mean value of 300 Wh/kg. This is aligned with the Chinese government’s target, as outlined in the 2020 updates to the technology roadmap for new energy vehicles\(^97\).

**Hydrogen fuel-cell truck.** The main parameter for a hydrogen fuel cell truck is the efficiency. Currently fuel cell has a peak energy efficiency of 60%, and the U.S. DOE has a goal to raise this to about 68% by 2030, and ultimately to 72%\(^98,99\). For this study we assumed a fuel cell efficiency of 67%, and a drivetrain and transmission efficiency of 90% similar to the battery electric truck, resulting in an overall FCT efficiency of 60% in 2030.

**Monte Carlo simulation:** To account for the variability of key parameters, a Monte Carlo simulation was applied. Each of these variables is assumed to follow a truncated normal distribution, within a bounded domain of known maximum and minimum values obtained from the literature (Table S3), or based on the limits of projected future values. Tables S4 and S5 summarize the values and ranges used for the 20,000 Monte Carlo iterations. This is a simplified uncertainty analysis, which only considers limited truck parameters as variables, and without assessing the covariance of variables. Therefore, the uncertainty ranges should be taken as indicative, which can be further refined in a more detailed analysis.

Figures S5, S6, and S7 provide a comparison between the energy consumption, fuel efficiency, and battery sizes derived from this study using Eq. 2 and the reported values in the literature for heavy-duty diesel trucks for the year 2016 and 2030, battery electric trucks, and hydrogen fuel cell trucks.

**Vehicle manufacturing (VLC).** Manufacturing and end-of-life recycling data for Class-8 heavy-duty trucks were extracted from Sphera’s LCA software and database (GaBi version 9.2 with 2020 LCI databases)\(^100\) for conventional diesel truck, battery-electric truck and hydrogen fuel-cell truck. The manufacturing emissions were updated to reflect the declining electricity carbon intensity profile projected for China in 2030. However, we assumed a constant value over time for the emissions associated with the manufacturing of raw materials given the lack of prospective and granular data in LCA databases for materials. The diesel truck has a net vehicle life cycle emissions of 34.8 tonne CO\(_{2e}\), which includes manufacturing emissions, vehicle maintenance and usage, and end-of-life recycling. For the electric truck, the battery requirement estimated from equation 2 corresponds to 260, 520 and 1100 kWh for an all-electric range of 240, 480 and 960...
The battery has a carbon intensity of about 78 kgCO$_{2eq}$/kg of battery$^{100}$. The net life cycle emission of the electric truck ranges between 99.9 and 312.8 tonne CO$_{2eq}$ depending on the battery size and total electric-range. The corresponding fuel cell truck has a net emission of 55.0 tonne CO$_{2eq}$, which includes the emissions associated with the manufacturing of an onboard, 700 bar hydrogen tank and fuel cell system. For all truck types, we assumed a total lifetime mileage of 800,000 km (or 500,000 miles)$^{101}$. Details of the manufacturing emissions and end-of-life recycling are provided in Figure S8.

**Fuels and energy productions (Cl$_e$). Traditional diesel.** Emissions due to oil extraction was obtained from Masnadi et al.$^{102,103}$, while refinery emission was taken from Jing et al.$^{104}$, resulting in a well-to-tank carbon intensity of 16.1 gCO$_{2eq}$/MJ of diesel.

**Synthetic low-carbon fuel.** There are limited, comprehensive life cycle emissions studies performed on synthetic low-carbon fuels derived from captured CO$_2$, which is an area of growing interest as a climate change mitigation tool. Here, we paired CO$_2$ from direct-air capture (DAC) with electrolytic hydrogen powered by renewable electric to produce syngas via the reverse water gas shift (rWGS) reaction, which is then converted into liquid hydrocarbons via the Fischer-Tropsch synthesis (FTS) process. The synthetic diesel can be used directly in an existing diesel engine. Detailed assumptions and estimation of the life cycle emission intensity of the synthetic low-carbon fuel is provided by Liu et al.$^{26}$, resulting in a well-to-tank and well-to-wheels carbon intensities of -44 gCO$_{2eq}$/MJ and 29 gCO$_{2eq}$/MJ respectively. Table S2 and Figure S4 provide an overview of recent LCA studies on synthetic electrofuels published in the literature with their key underlying assumptions. We assessed the impacts of adopting different carbon intensity values on the overall GHG emissions of the heavy-duty truck (Figure 5).

**Electricity generation.** We adopted the International Energy Agency’s (IEA) 2019 World Energy Outlook (WEO) report$^4$ to obtain the projected grid mix in China for the year 2030. The base case is based on IEA’s Stated Policy Scenario (SPS) with a total electricity generation of 10,177 TWh, with coal, natural gas, nuclear, and renewables each accounting for 51%, 7%, 6%, and 36%, resulting in an average electric carbon intensity of 626 gCO$_{2eq}$/kWh$^4$. For battery electric trucks, we performed a sensitivity analysis using different grid mix based on the IEA’s Current Policy Scenario (CPS) and Sustainable Development Scenario (SDS) with electric carbon intensities of 645 and 483 gCO$_{2eq}$/kWh respectively$^4$. Details of the grid mix for the different scenarios are provided as Figure S9. An efficiency of 96% was assumed for charging the battery in the electric truck.

**Hydrogen productions.** Seven hydrogen production pathways that are common in China were included in the analysis. The carbon intensities for the 7 pathways below include hydrogen transport and distribution via a tube trailer over a distance of 400km$^{23}$. Data sources for each hydrogen pathway are referenced, and for comparison purposes, the resulting carbon intensities are contrasted against the U.S. Argonne National Laboratory’s GREET Model (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies), version 2019$^{105}$ in Table S6.
Coal gasification. China has plenty of coal resources that is currently used for hydrogen production\(^3\). This pathway involves the gasification of coal and a shift-conversion reaction to produce hydrogen. Data for hydrogen production via coal gasification specific to the Chinese market was obtained from Hao et al\(^2\), in which the hydrogen has a carbon intensity of 34.4 kgCO\(_{2eq}/\)kg-H\(_2\)\(^2\).

By-product of coke-oven-gas (COG). China has a large coke production and consumption industry. The production process is based on an existing COG hydrogen plant in China’s Inner Mongolia\(^1\), which produces coke, COG, coal tar and crude benzene. Allocation was done using their respective commodity market value. Detailed life cycle data for the production of COG hydrogen can be obtained from Li et al\(^1\), in which the resulting carbon intensity used in this study is 18.1 kgCO\(_{2eq}/\)kg-H\(_2\). Since the COG has a higher volumetric hydrogen content (>50%), its carbon intensity is lower than the hydrogen produced via coal gasification.

Biomass-to-hydrogen. The use of biomass for hydrogen production is not expected to play a big role in China in the year 2030. The thermochemical hydrogen production route involves the gasification of corn stover to produce syngas, and followed by a water gas shift reaction to increase the hydrogen yield\(^1\). The life cycle assessment details for the biomass-to-hydrogen process are provided by Li et al\(^1\), which resulted in a carbon intensity of 9.6 kgCO\(_{2eq}/\)kg-H\(_2\).

Alkaline-water electrolysis. Hydrogen production via electrolysis accounts for about 1% in China today\(^3\), but it is expected to grow to 15% by 2030\(^3\). Today, the electrochemical splitting of water is done mainly using the average grid electricity. However, the China Hydrogen Alliance \(^3\) projects that this will be powered by wind-generated electricity in 2030. The alkaline electrolysis process was modelled by modifying an existing pathway in Sphera’s LCA software and database (GaBi version 9.2 with 2020 LCI databases)\(^1\), resulting in carbon intensity values of 36.8 and 4.9 kgCO\(_{2eq}/\)kg-H\(_2\) for hydrogen produced using China’s grid average and wind-powered electrolysis respectively.

Steam Methane Reforming (SMR). Worldwide, natural gas reforming accounts for almost 50% of hydrogen production, however in China it is responsible for less than 20% in 2016\(^3\). The scarcity of gas reserves in China\(^1\),\(^1\) makes hydrogen production via SMR less attractive. Hydrogen production by SMR was extracted from Sphera’s LCA software and database (GaBi version 9.2 with 2020 LCI databases)\(^1\), with a carbon intensity of 15.8 kgCO\(_{2eq}/\)kg-H\(_2\).

By-product of chlor-alkali. The chlor-alkali industry is considered one of the most promising low-cost hydrogen sources in the near-term\(^4\), with niche potential particularly in regions surrounding the industry\(^3\). The electrolysis of aqueous sodium chloride leads to the co-production of sodium hydroxide and chlorine, with hydrogen as a by-product\(^4\). By performing mass-based allocation, the hydrogen carries a carbon intensity of 5.5 kgCO\(_{2eq}/\)kg-H\(_2\)\(^2\).
\[ W_L = GVW - W_v - \left( \frac{E_p}{S_p \times f_{pack}} \right) \]  
(Equation 3)

Where:

- \( W_L \) = maximum payload
- \( GVW \) = gross on-road vehicle weight
- \( W_v \) = empty vehicle weight
- \( E_p \) = Vehicle energy demand
- \( S_p \) = specific energy of fuel/battery
- \( f_{pack} \) = packing burden factor (additional weight for the thermal management systems, module hardware, battery jackets, and other non-cell inactive materials used to assemble a practical battery pack).

**Lifecycle and freight efficiency.** Three methods for estimating freight efficiencies were adopted as per the following definitions.

**Freight efficiency:** This is a measurement of freight efficiency at a vehicle level in payload tonne-km per liter of diesel equivalent. It is similar to the standard industry method of measuring freight efficiency in tonne-miles per gallon.

**Lifecycle energy consumption:** In this method, we estimated the total energy consumed from well-to-wheels (WTW) to transport one tonne of payload over one km distance, and measured in MJ/tonne-km. The total WTW energy consumption takes into account the vehicle energy use, and the total energy required to produce 1MJ of the fuel (diesel, hydrogen and electricity), but it does not take into consideration the energy consumed in the vehicle lifecycle (i.e. vehicle production, battery manufacturing, and vehicle EOL recycling). For diesel fuel, this includes the energy used in crude oil extraction, refining and distribution. In the case of electricity generation and hydrogen production, the energy consumption starts from primary energy for exhaustible resources (coal, natural gas, nuclear) by taking into account of their thermal energy contents, meanwhile for renewable energy (i.e. wind and solar), the energy consumption starts from the secondary energy (i.e. generated electricity) consistent with the approaches taken in literature\(^{111}\). This is because wind and solar energies are inexhaustible.

**Lifecycle efficiency:** The overall lifecycle efficiency, in percentages, measures the cumulative efficiency (and losses) throughout the multiple energy transformation steps from well-to-wheels (WTW). Given that it tracks the energy output/input for each step, lifecycle efficiency does not take into consideration of the payload implications. The calculation method is similar to the lifecycle energy consumption: for diesel fuel, it includes the efficiencies of crude oil extraction, refining, distribution and vehicle use. In the case of electricity generation and hydrogen production, the efficiency calculation begins from the transformation of primary energy for exhaustible resources (coal, natural gas, nuclear) by taking into account of their thermal energy...
contents, meanwhile for renewable energy (i.e. wind and solar), the efficiency calculation starts from the secondary transformation (i.e. electricity generation is considered 100%) consistent with the approaches taken in literature. This is because wind and solar energies are inexhaustible and therefore the efficiency measurement for the conversion of wind/solar to electricity is less useful in the discussion of climate change, though it is a relevant measure for the profitability of energy companies.

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Author Contributions


Declaration of Interests

The authors declare no competing interests.

References


Saudi Aramco: Public


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**Figure 1** Climate change mitigation potential of different Class-8 HDTs in China in 2030. The emissions of CO$_2$ measured on a life cycle basis in gCO$_{2eq}$/tonne-km for high-efficiency combustion-based truck fueled by diesel (HET-D) and low-carbon fuel (HET-LCF), battery-electric trucks (BET) powered by the average grid mix in China in 2030 based on the IEA’s Stated Policy Scenario (IEA SPS), Current Policy Scenario (IEA CPS) and Sustainable Development Scenario (IEA SDS), and fuel cell trucks (FCT) using different hydrogen sources. The projected hydrogen supply mixes for China in 2030 are based on three scenarios developed by the China Hydrogen Alliance$^{33}$. [Coal gas. = coal gasification; COG = coke oven gas; SMR = steam methane reforming].

**Figure 2** Implications of haulage distances on truck payloads. (A) Payload implications for different powertrain types with increasing truck mileage range. The battery size requirements for the electric trucks are 260, 520, and 1100 kWh to fulfill the all-electric ranges of 150, 300, and 600 miles respectively. (B) Effects of increasing the GVW allowance of an electric truck on its ability to retain the maximum payload capacity estimated relative to a comparable diesel truck. (C) Effects of haulage distance on the total life cycle GHG emissions of different energy-powertrain combinations (D). Life cycle GHG emissions breakdown of battery-electric trucks with the corresponding battery sizes to fulfill the all-electric range requirements. Results for an HDT with a GVW of 31.5 tonne. Results for other GVW categories are shown in Figure S1.

**Figure 3** Estimated charging durations for electric trucks. Charging of electric trucks with different battery sizes (and electric ranges) using three types of chargers: 150kW, 350kW, and 1000kW with a 96% charging efficiency.

**Figure 4** Lifecycle energy efficiencies of battery-electric and fuel-cell trucks. Breakdown of overall lifecycle energy efficiencies into major energy conversion steps. Two different scenarios were evaluated: a scenario based on the likely energy mix in China by 2030, and a scenario where only wind-electricity is used. For wind generated electricity, the efficiency is considered to be 100% since the resource is unlimited and available regardless if it is used or not$^{111}$. 
Figure 5 Effects of fuel carbon intensity and engine efficiency on the life cycle GHG emission of combustion-based HDT. (A) The carbon intensity of low-carbon synthetic fuel at varying power generation emission intensity based on data from Liu et al.\textsuperscript{26}. This study adopted a value of 29 gCO\textsubscript{2eq}/MJ corresponding to an electric carbon intensity of about 13 gCO\textsubscript{2eq}/kWh. Extended literature references are provided in Table S2 and Figure S4. (B) Effects of varying the fuel carbon intensity on the total life cycle GHG emission of a diesel-engine truck. (C) Effects of the engine break thermal efficiency on the total life cycle GHG emission of a diesel-engine truck.

Figure 6 GHG emission of an electric truck as a function of the projected grid carbon intensity. Effects of varying the projected grid carbon intensity in China for 2030 on the overall life cycle GHG emissions of electric trucks with battery sizes of 260kWh, 520kWh, and 1100kWh, corresponding to 150miles, 300miles, and 600miles electric range respectively.

Figure 7 Life cycle GHG emissions of an electric truck with different hydrogen supply sources. The GHG reduction potential of China’s low carbon hydrogen, clean hydrogen, and renewable hydrogen, as defined by its life cycle GHG standard for hydrogen.