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How do we decarbonize one billion vehicles by 2050? Insights from a comparative life cycle assessment of electrifying light-duty vehicle fleets in the United States, China, and the United Kingdom

Da Huo [a], Ben Davies [b], Jianxin Li [c], Nadine Alzaghrini [a], Xin Sun [c], Fanran Meng [d], Amir F.N. Abdul-Manan [e], Jon McKechnie [b], I. Daniel Posen [a], Heather L. MacLean [a,*]

[a] Department of Civil & Mineral Engineering, University of Toronto, Toronto, ON, M5S 1A4, Canada
[b] Sustainable Process Technologies, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, United Kingdom
[c] China Automotive Technology and Research Center Co, Ltd, No. 68 East Xianfeng Road, Dongli District, Tianjin, 300300, China
[d] Department of Chemical & Biological Engineering, Sir Robert Hadfield Building, The University of Sheffield, Sheffield, S1 3JD, United Kingdom
[e] Strategic Transport Analysis Team, Transport Technologies R&D, Research & Development Center (R&D), Saudi Aramco, Dhahran, 31311, Saudi Arabia

A B S T R A C T

Electrifying light-duty vehicle fleets is essential to decarbonize road transport, however its efficacy relies on policies targeting country-specific challenges and opportunities. We model and compare fleet-level life cycle GHG emissions for different grid scenarios and battery electric vehicle deployment timelines respectively in the US, China, and the UK from 2020 to 2050, cumulatively involving over one billion vehicles. A customized index decomposition analysis is employed to quantify the contributions of key emissions drivers. Results reveal that electrification can be effective for decarbonizing all three fleets, reducing over 50% of annual life cycle emissions by 2050. Priorities and challenges, however, differ across countries: The US fleet, which emits the highest GHGs, generally comprises older, heavier, and less fuel-efficient vehicles, would benefit the most from electrification and fleet modernization. Grid decarbonization and managing car ownership growth are critical for China, as its rapidly growing fleet and manufacturing rely on currently carbon-intensive electricity. The UK needs to expand its electricity generation capacity while electrifying its fleet. We also underscore the need for a comprehensive strategy, including electrification, low GHG intensity fuels, and moderating vehicle ownerships. This study highlights the importance of cross-country life cycle thinking to inform effective decarbonization policy decisions.

1. Introduction

This paper presents a cross-country comparison of light-duty vehicle (LDV) fleet decarbonization through electrification using life cycle assessment models developed for the US, China and the UK. The transport sector is one of the largest contributors to global greenhouse gas (GHG) emissions. Within the United States (US), this sector alone emitted 1800 $MtCO_2eq$ in 2022, which accounted for 28% of the country's total direct fossil fuel GHG emissions, and 57% of these emissions were generated by LDVs (EPA, 2024). In the United Kingdom (UK), the transport sector produced 26% (110 $MtCO_2eq$) of the total fossil fuel GHG emissions in 2021 (UK Department for Transport, 2023). In China, the transport sector accounts for 9% (900 $MtCO_2eq$) of the total GHG emissions (Automotive Data of China Co., Ltd. 2023; Zhang et al., 2024). The absolute transport GHG emissions in China are comparable to the US and the European Union (EU) but are growing at a much faster pace (Xue et al., 2023). Transitioning to a lower-carbon mobility options will be key to mitigate GHG emissions in most countries, and electrifying light-duty vehicle (LDV) fleets is currently considered one of the most promising pathways (Milovanoff et al., 2020)

Three countries, the US, China, and the UK are selected and compared in this study as the US, China and Europe are among the largest markets for LDVs globally (IEA, 2023), accounting for around 500 million vehicles on the road today and over 1 billion considering turnover by 2050; as such, their actions towards decarbonization can have a significant impact on global emissions. The UK is selected as an example from Europe as it is relatively straightforward to isolate for a country-level analysis and is among the most populous European countries. These three countries are compared also because they have very different fleets, representing two developed countries (the UK has a smaller and greener fleet with a low-carbon grid, while the US is an efficiency/environmental laggard with the highest-emission fleet) and one developing country (China) with the world's fastest-growing fleet and a relatively carbon-intensive grid. Assessing how these three different fleets respond to electrification can provide insights into the global landscape of LDV fleet decarbonization efforts.

* Corresponding author.
E-mail address: heatherl.maclean@utoronto.ca (H.L. MacLean).

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Electric vehicle (EV) adoption policies have been formulated across the world in recent years. In the US, several states have set their EV targets, for example, California has set a goal for 100% of in-state new vehicle sales to be zero-emission vehicles by 2035 (California Air Resources Board, 2023a), New York and New Jersey are also setting similar targets (New York State Governor, 2022; State of New Jersey Governor, 2023). On a federal level, there are plans to increase the fuel efficiency of vehicles and to offer incentives for EV purchases, but a specific timeline for phasing out gasoline and diesel vehicles has not been established. Compared with China and the UK, the adoption of EVs in the US is relatively low with EVs only accounting for 4.5% of total new LDV sales in 2021 but has been increasing in recent years due to government incentives and consumer demand (Davis and Boundy, 2022).

China has set ambitious targets for EV adoption and is the largest market for EVs globally. Various incentives such as subsidies and tax exemptions have been implemented in China to encourage the adoption of EVs (Sun et al., 2020). The government has also invested heavily in the development of charging infrastructure, further encouraging the adoption of EVs (Sun et al., 2020). Consequently, China stands out with one of the highest EV penetration rates among all major markets. In 2022, China's New Energy Vehicles (NEVs, which are mostly EVs, also including other vehicles that are not mainly powered by fossil fuel) market share achieved 25.6% based on the China Association of Automobile Manufacturers (CAAM). This surpassed the country's goal of having NEVs account for at least 20% of new car sales by 2025 and 50% by 2035 (General Office of The State Council People's Republic of China, 2020; S&P Global, 2020). Projections for the Chinese market indicate that by 2030, 40% (Stauffer, 2021) to 50% (S&P Global, 2023) of new vehicle sales will be electric, and BEV sales could reach 76% by 2035 (IEA, 2024a).

The UK government has also implemented various grants and tax credits to encourage the adoption of EVs, and consumer demand for these vehicles has been increasing. The UK government aims to move faster than any other major economy in decarbonizing the transport sector and has set an aggressive target to end the sale of new petrol and diesel vehicles by 2030 (Government of the UK, 2020). However, this has been postponed to 2035 in a recent UK policy reversal to be more aligned with the European Union and other countries worldwide.

To enhance the adoption of EVs, a variety of policy instruments beyond targets are being implemented (IEA, 2024a; ICCT, 2023). These include legislation such as legally binding commitments for manufacturers to produce a certain percentage of zero-emission vehicles (ZEVs), and financial incentives like reduced taxes and subsidies for EV purchasers. Additionally, infrastructure development policies, categorized under electric vehicle supply equipment are crucial, facilitating the installation of charging stations to support the growing number of EVs. These measures include both binding regulations and targets to drive a transition towards electric mobility.

Life cycle assessment (LCA) is a tool increasingly used for assessing GHG emissions of zero tailpipe emission vehicles like EVs (Sun et al., 2019; Tarabay et al., 2023; Wu et al., 2018), since emissions associated with EVs are mostly derived from non-vehicle-use stages, including battery production and electricity consumption (Ellingsen et al., 2016; Faria et al., 2012; Hawkins et al., 2013). LCA-based approach offers a more comprehensive comparison of alternative fuel and vehicle technologies (Hackney and de Neufville, 2001). When modeled at a fleet-level, it allows the identification of bottlenecks at a system's level, for example a low EV adoption rate or vehicle turnover rate in the market, which provides additional information to decision-makers to better address challenges associated with specific life cycle stages (Wu et al., 2019). Fleet-level LCA is increasingly used to gain new insights on the decarbonization potential and implications of fleet electrification. A recent modeling of the US LDV fleet found that electrification alone will not meet emission mitigation requirements (Milovanoff et al., 2020) and will likely face critical metal demand issues (Tarabay et al., 2023). Recent studies for China suggested that LCA-based fleet emission standards should replace tail-pipe-based standards for more effective decarbonization strategies to avoid burden shifting (Xue et al., 2023), and better address the regional differences in grid intensity and charging infrastructures (Wu et al., 2019). In this study, we combine the Fleet Life Cycle Assessment and Material-Flow Estimation (FLAME) model originally developed for the US (Milovanoff, 2019; Milovanoff et al., 2020) with newly developed versions for the UK and China (referred to as FLAME-US, FLAME-UK and FLAME-CN) to enable a comprehensive cross-country comparison of fleet-level decarbonization through electrification as a means to draw policy-relevant insights.

The lack of cross-country/region comparisons of decarbonization through electrification from a fleet-LCA perspective is a major research gap that limits our understanding of country-specific challenges and opportunities. Existing cross-country comparisons of fleet electrification, such as reports from the International Energy Agency (IEA, 2023), provide a broad overview of the transition's implications for direct GHG emissions. These studies encompass various EV technologies and energy transition scenarios across multiple regions. However, they do not take a fleet-level LCA perspective, which is the key objective of this work. Prior LCA studies have primarily focused either on fleets in a single country (Milovanoff et al., 2020; Xue et al., 2023) or on single vehicle-level comparisons (Hao et al., 2017; Huo et al., 2015; Wu et al., 2018), which do not provide fleet-level contrasts to help benchmark a country's performance. This study aims to apply country-specific fleet LCA models with scenario-based projections, offering detailed insights into the diverse priorities and bottlenecks of light-duty vehicle fleet decarbonization in different countries, highlighting the need for tailored policy interventions in each context. This study also aims to determine whether some EV and decarbonization policies are generalizable across countries.

Furthermore, there is still a gap in knowledge on how the key factors that contribute to life cycle emissions would differ across countries and time, particularly in a drive to electrify the LDV fleet. Quantifying drivers of change in fleet life cycle emissions over time and across geographies requires immediate attention to ensure that appropriate policy levers can be designed using market-specific characteristics, and deployed timely, to enable maximum effectiveness. Typically, existing approaches predominantly concentrate on explicit factors like vehicle fuel consumption and emission factors. These, however, do not necessarily reflect the complexity of an evolving fleet, particularly when subjected to a broader driver of change, such as electrification, that cuts across multiple life cycle stages. One potential solution is using index decomposition analysis, which decomposes emission changes into multiple drivers (Huo et al., 2023; Rasul and Hertwich, 2023). However, existing index decomposition schemes only address vehicle-use emissions that neglect other life cycle stages (Papagiannaki and Diakoulaki, 2009). To address this issue, we develop a life cycle Logarithmic Mean Divisia Index (LMDI) approach in this study that decomposes fleet emissions into multiple drivers across multiple life cycle stages to identify and compare key factors that influence the success of electrification efforts and supports in-depth cross-country comparisons.

This study uses life cycle fleet GHG emission modeling and index decomposition analysis to compare the projected efficacy of LDV fleet decarbonization through electrification in the US, China, and the UK. We first present a cross-country comparison of key fleet and vehicle characteristics, and then we model and compare the annual and cumulative GHG emissions to highlight and compare the respective fleets' responses to different electrification timelines and grid decarbonization scenarios. An innovative LMDI decomposition scheme is then adopted to quantify the contributions from factors that are driving emissions changes for each fleet and are presented as both temporal (interannual) profiles and spatial (cross-country) profiles. We then provide cross-country comparisons of electricity demand, GHG reduction per kWh battery, and analysis of equivalent GHG reductions from low carbon fuels. In discussions and conclusions, we offer country-specific priorities, challenges, and opportunities associated with LDV fleet electrification, and provide policy recommendations to enable a more effective decarbonization of the transport sector in each country.

2. Methodology

2.1. Fleet Life Cycle Assessment and Material-Flow Estimation (FLAME) model

Life cycle GHG emissions for each fleet are modeled using country-specific Fleet Life Cycle Assessment and Material-Flow Estimation (FLAME) models. The FLAME model was originally developed for the US fleet by (Milovanoff, 2019) and was updated in (Milovanoff et al., 2020). The model has four dynamically connected modules: 1. Vehicle, 2. Fleet, 3. Material flow, and 4. Life cycle assessment (Fig. 1) which are detailed in (Milovanoff, 2019). The model uses LCA as a tool for the fleet-level GHG emissions quantifications and incorporates vehicle turnover rate to renew the fleet over time based on their survival patterns. Life cycle stages modeled in this study include: 1. Materials production, which quantifies the emissions associated with the production of the raw materials used in the vehicle. 2. Fuel production, which covers the emissions generated during fuel production (gasoline, diesel, and electricity in this study). 3. Vehicle and battery production, which focuses on the emissions associated with the production of the vehicle and battery, including the energy used in the manufacturing process and the emissions associated with the production and end-of-life management of components. 4. Vehicle use, which quantifies the tailpipe emissions generated from engine fuel combustion and grid electricity consumed during an EV's on-road use. FLAME models a variety of vehicle powertrains, such as gasoline-powered internal combustion engine vehicles (ICEV-G), diesel-powered internal combustion engine vehicles (ICEV-D), battery electric vehicles with a 300-mile range (BEV300), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), fuel cell vehicles (FCV) and compressed natural gas vehicles (CNG). Given the study's focus on electrification, and that the two main powertrain technologies (ICEV and BEV) together account for over 90% of both current and projected fleets, the analysis mainly contrasts ICEV and BEV, grouping the rest of the vehicles under 'Others'. We focus on two projected paths for the LDV technology mix: 1. Electrification, in which the new vehicle sales shares of all powertrain technologies other than BEV decrease linearly over time, and 2. Fixed share, in which the new vehicle sale shares of all powertrain technologies are fixed at their 2022 levels.

The FLAME model has been described and applied in prior literature (Milovanoff, 2019; Milovanoff et al., 2020; Tarabay et al., 2023; Alzaghrini et al., 2024). Additional steps taken toward validating the model are described in the SI (Section 6). Besides the original FLAME-US model, models for the Chinese fleet (FLAME-CN) and the UK fleet (FLAME-UK) are constructed following the same structure (Fig. 1) and are populated with country-specific historical data and projections, providing the capabilities of modeling dynamic fleet structure changes and life cycle GHG emissions of different vehicle technologies from 2020 to 2050 in each country. Model availability is discussed in SI section 3.2.

2.1.1. FLAME-US

The US version of the FLAME estimates the projected GHG emissions of the US LDV fleet and enables the assessment of GHG emissions and material use associated with different vehicle technologies (e.g., BEV, ICEV, etc.), behavioral patterns (e.g., vehicle kilometer traveled), or policy variations (e.g., the 2035 BEV plan). Key model inputs and projections are adopted from EIA's Annual Energy Outlook (U.S. Energy Information Administration, 2022) and the GREET model (Wang et al., 2021). A detailed list of these model parameters and sources is provided in Table 1.

Several changes to the original FLAME-US model were made in this study: 1. Historical data were updated to 2022, e.g., 2022 grid intensity from EPA's eGrid (EPA, 2023a). 2. The grid mix projections is updated with EIA's latest reference case in the Annual Energy Outlook 2023 (U.S. Energy Information Administration, 2023), which is a more ambitious grid decarbonization projection than in prior model. 3. Fuel

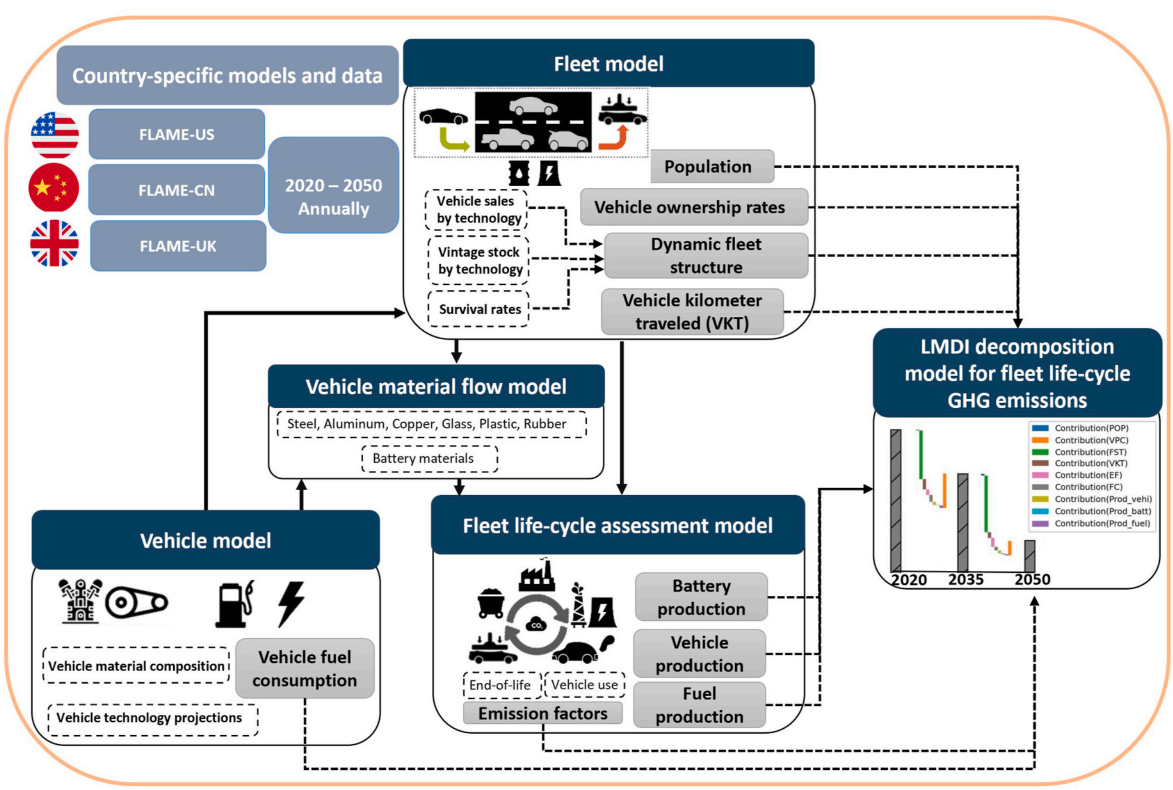

Fig. 1. The overall structure of the Fleet Life Cycle Assessment and Material-Flow Estimation (FLAME) models for the US, China and the UK fleets, and the connections with a life cycle Logarithmic Mean Divisia Index (LMDI) decomposition model.

Table 1
Key model inputs and sources for FLAME-US, FLAME-CN, and FLAME-UK.

	FLAME-US	FLAME-CN	FLAME-UK
Prior models	FLAME (Milovanoff, 2019), and updated in (Milovanoff et al., 2020)	China Automotive Life Cycle Assessment Model (CALCM) (Automotive Data of China Co.Ltd, 2023; Wu et al., 2019)	–
Stock projections	Projections from the EIA's Annual Energy Outlook (U.S. Energy Information Administration, 2022)	Calculated based on population and GDP following SI Eqs. (1) and (5)	Calculated based on (Office for National Statistics, 2022), following SI Eq. 6
Vehicle sales projections	Calculated based on stock projections and vehicle survival rates as per (Milovanoff, 2019)	Calculated based on stock and scrappage projections, following SI Eq. 4	Calculated using the electrification policy scenario and following SI Eq. 9
Survival rate of vehicles	Adopted from the Transportation Energy Data Book (TEDB) (Davis and Boundy, 2021)	Calibrated from the historical passenger vehicle population data (CTALI) by technology and age from 2012 to 2020 in China	Fixed distributions; calculated from historical vehicle statistics following fleet average (Department for Transport, 2022a)
Vehicle kilometer traveled (VKT)	Historical and projections: Adopted from TEDB, defined for vehicle age. Each powertrain is represented uniquely.	Adopted from a recent study (Ou et al., 2020). Each powertrain is represented uniquely.	Fixed value; ICEV-G and ICEV-D represented uniquely, other powertrains following fleet average from the Department for Transport National Travel Survey 2022 (Department for Transport, 2022b)
Average vehicle mass	Historical: Adopted from the GREET model (Wang et al., 2021). Projections: fixed value	Historical: CTALI Projections: fixed value	Historical: Calculated from international vehicle testing (European Environment Agency, 2020). Projections: fixed value
Energy consumption of BEVs and ICEVs	Historical: Annual Energy Outlook (U.S. Energy Information Administration, 2022). Adapted based on local test cycle (Milovanoff et al., 2020) Projections: 1% annual improvement for ICEVs, 1.5% annual improvement for BEVs	Historical: Annual Report on Energy-Saving and New Energy Vehicles in China (CATARC, 2021). Adapted based on China Light-Duty Vehicle Test Cycle Projections: 1% annual improvement for ICEVs, 1.5% annual improvement for BEVs	Historical: calculated from international vehicle testing (European Environment Agency, 2020). Adapted based on World Light Vehicle Test Cycle Projections: 1% annual improvement for ICEVs, 1.5% annual improvement for BEVs
Emission factors for the production of primary metals (in both vehicle body and battery)	Historical and projections: Adopted from the GREET model (Wang et al., 2021)	Historical: Adopted from CALCD Projection: Adopted from CALCP	Common materials use fixed values from (Wernet et al., 2016) Battery materials projections from (Llamas-Orozco et al., 2023)
Vehicle material composition considered	Steel, Aluminum, Copper, Glass, Plastic, Rubber (96.7% of vehicle mass based on GREET model)	Steel, Aluminum, Copper, Glass, Plastic, Rubber	Steel, Aluminum, Copper, Glass, Plastic, Rubber
Emission factors for gasoline and diesel production	Historical: Adopted from the GREET model (Wang et al., 2021) Projections: fixed value	Historical: Adopted from CALCDProjections: fixed value	Fixed values; from (Wernet et al., 2016)
Grid mix	Historical grid intensity: Adopted from EPA eGRID; Grid mix under decarbonization projections: Adopted from EIA's Annual Energy Outlook 2023 reference case (U.S. Energy Information Administration, 2023)	Historical: Adopted from CALCD Projection: Adopted from CALCP	Projected grid emissions intensity from (National Grid Electricity System Operator Limited, 2022)
Emission factors of fossil fuel combustion	Historical: Adopted from the GREET model (Wang et al., 2021) Projections: fixed value	Historical: Adopted from the CALCDProjections: fixed value	Fixed value; average fuel blends from (Department for Environment Food & Rural Affairs, 2021)
Emission factors for vehicle body manufacture	Historical and projections: Adopted from the GREET model (Wang et al., 2021)	Historical: Adopted from CALCD Projection: Adopted from CALCP	Historical and projections from (Wernet et al., 2016)
Emission factors for BEV battery manufacture	Historical: Adopted from the GREET model Projections: Adopted the annual change rate of grid emission intensity	Historical: Adopted from CALCD Projection: Adopted from CALCP	Historical and projections from (Llamas-Orozco et al., 2023)

consumption assumes 1% annual improvement for ICEVs and 1.5% annual improvement for BEVs following FLAME-CN, which is within the plausible ranges for US scenarios (Alzaghrini et al., 2024). 4. BEV batteries are assumed to be manufactured in China which is closer to current reality than assuming domestic production (Tarabay et al., 2023).

2.1.2. FLAME-CN

The China (CN) version of the FLAME model (FLAME-CN) is developed by updating the LCA module with the China Automotive Life Cycle Assessment Model (CALCM) (Automotive Data of China Co.Ltd, 2023; Wu et al., 2019) and using the China-specific database for both the fleet characteristics and the emission factors. The historical passenger vehicle data is sourced from the China Compulsory Traffic Accident Liability Insurance for Motor Vehicles (CTALI) database (Yu et al., 2022). The CTALI database covers all on-road vehicles in China; with data encompassing, but not limited to, the vehicle type, powertrain, vehicle age, curb weight, fuel consumption rate, traction battery weight, and traction battery capacity. The historical stock includes information on the year of data collection, the year of production, vehicle type, powertrain, and vehicle age. The LCA data is primarily acquired from the China Automotive Life Cycle Database (CALCD) (Sun et al., 2019, 2020; Wu et al., 2018), which is the China-specific life cycle inventory (LCI) database developed by the China Automotive Technology and Research Center Co., Ltd. (CATARC) that covers more than 20,000-unit processes (e.g., metals, minerals, plastics, water, chemicals, fuels, energy production, etc.) and life cycle data for automotive parts and vehicles. Projections on grid and vehicle material emission factors are adopted from the China Automotive Low Carbon Action Plan 2022 (CALCP) (Automotive Data of China Co., Ltd., 2023).

2.1.3. FLAME-UK

The UK version of the FLAME model (FLAME-UK) is a redevelopment based on the original FLAME model (Milovanoff, 2019), to evaluate the GHG emission and material flow implications of policy decisions in the UK transport sector. Vehicle attributes are sourced from the EU database for emissions testing (European Environment Agency, 2020) representing generally smaller vehicles than those found in the North American fleet. Historic fleet data is sourced from the Department for Vehicle Licensing Vehicle Statistics Database (Department for Transport, 2022a). This informs the existing LDV fleet at the beginning of the simulation, and the empirical survival rate by age for all vehicles in the UK. The UK fleet has a much higher proportion of ICEV-D than is found in the other regional fleets, a result of past government policies encouraging the sale of ICEV-D, which emits less CO_2 per km traveled. The future fleet size is predicted through a population projection (Office for National Statistics, 2022) and the expected rate of ownership, with new sales distributed based on the input electrification sales market scenarios. Beyond the regional database for fleet composition, the FLAME-UK model has been extended with details for electric vehicle battery materials and manufacture, building on the prior work (Llamas-Orozco et al., 2023)

2.2. Data collection

In this study, the models use actual historical fleet data up to the year 2022 as the starting point for projections. A list of sources for historical data and projections is provided in Table 1. Additional information about the timespan and attributes of the historical input data is available in Table S1. We adjust the inputs in each FLAME model to ensure consistent modeling assumptions and comparable outcomes. We model light-duty trucks as part of the LDV fleet in accordance with the U.S. definition of light-duty passenger vehicles (gross vehicle weight <3856 kg). Further, we build the reference case scenario on fixed powertrain market share projections from 2020 through 2050, in contrast to a business-as-usual (BAU) scenario as the assumptions associated with BAU can vary significantly across countries. The Supplementary Information (SI) presents the comparisons of key input data, such as new vehicle sales (Fig. S1), vehicle ownership rate (Fig. S2) and grid GHG intensity (Fig. S3). Some uncertainties exist across the three models as country-specific projections are adopted from different sources (Table 1) which could imply different assumptions. A sensitivity analysis is provided in the SI that estimates the uncertainty ranges caused by different projections of fuel efficiency (Fig. S4) and fuel efficiency improvement projections from different sources (Table S2), vehicle manufacture emissions (Fig. S5), and battery manufacture emissions (Fig. S6) for each country. For each parameter, we model a reference case in the main paper along with an optimistic case (large improvements), and a pessimistic case (no improvements beyond 2023) in the SI.

2.3. Index decomposition model for fleet life cycle emissions

To quantify the impact of various drivers in the change of fleet life cycle emissions, we develop a customized index decomposition approach. Decomposition analysis is one of the most effective methods for understanding the factors that are driving changes in energy and industrial systems (Ang, 2004, 2005). The Logarithmic Mean Divisia Index (LMDI) decomposition has been favorable due to its advantages in interpretation simplicity, consistency in aggregation, and good handling of zero values (Guan et al., 2018). Multiple studies have successfully used LMDI to understand the drivers of the carbon footprint (Huo et al., 2023; Rasul and Hertwich, 2023). Existing LMDI schemes, however, do not support the decomposition of life cycle emissions. To address this issue, a customized life cycle LMDI scheme is proposed in this study (Eq. (1)):

$$GHG^t = POP^t \cdot VPC^t \cdot \sum_s \sum_p FST^t_{s,p} \cdot EF^t_{s,p} \cdot VKT^t_{s,p} \cdot FC^t_{s,p} \cdot P_{batt}{}^t_{s,p} \cdot P_{fuel}{}^t_{s,p} P_{vehicle}{}^t_{s,p}$$

$$= POP^t \cdot VPC^t \cdot FST^t_{b\_manuf,EV} \cdot P_{batt}{}^t_{EV} \quad (s = battery\ manufacture\ stage) + \ldots$$

$$POP^t \cdot VPC^t \cdot \sum_p FST^t_{v\_manuf,p} \cdot P_{vehicle}{}^t_p \quad (s = vehicle\ manufacture\ stage) + \ldots$$

$$POP^t \cdot VPC^t \cdot \sum_{ICEV} FST^t_{P_{fuel},ICEV} \cdot P_{fuel}{}^t_{ICEV} \quad (s = fuel\ productiom\ stage) + \ldots$$

$$POP^t \cdot VPC^t \cdot \sum_p FST^t_{use,p} \cdot EF^t_{use,p} \cdot VKT^t_{use,p} \cdot FC^t_{use,p} \quad (s = vehicle\ use\ stage) \tag{1}$$

Where:

- GHG^t represents fleet GHG emissions in year t;
- *POP* represents population;
- *VPC* represents number of vehicle per capita (ownership);
- *s* stands for vehicle life cycle stages (e.g., manufacture, use);
- *p* stands for powertrain type (e.g., BEV, ICEV-G, ICEV-D);
- *FST* is the fleet structure mix in that year, which represents new vehicle share or powertrain mix based on the given life cycle stage. For instance, it equals the share of new BEVs in the fleet ($FST^t_{b\_manuf,EV}$) for the battery manufacture stage, and for the vehicle use stage, it represents the share of each powertrain in the fleet ($FST^t_{use,p}$);
- *EF* represents GHG emission factors from vehicle use, which also varies based upon the powertrain (e.g., grid emission factor for EV, gasoline emission factor for ICEV-G);
- *VKT* represents the average annual Vehicle Kilometers Traveled for each powertrain in that year;
- *FC* represents the average per unit fuel consumption for each powertrain in that year, which also varies based upon the powertrain (e.g., grid emission factor for EV, gasoline emission factor for ICEV-G);
- P_{batt}, P_{fuel}, *and* $P_{vehicle}$ represent the average per unit emissions for battery, fuel and vehicle production respectively.

In the decomposition, end-of-life stage is not listed as a contributing factor although the related processes are modeled (e.g., recycling) because our data do not capture its changes for each powertrain and emissions from vehicle dismantling are relatively small (the full end-of-life process is not modeled). For manufacture stages, all the on-road transport factors (*EF, VKT, FC*) are set to be 1, this also applies to other life cycle stages to attribute contributing factors to the appropriate life cycle stage. For the vehicle-use stages, all the manufacturing factors (P_{batt}, P_{fuel}, $P_{vehicle}$) are set to be 1.

Therefore, the changes in annual emissions can be represented as the sum of nine components: 1. change in population (ΔPOP), 2. change in vehicle per capita (ΔVPC), 3. change in fleet structure (ΔFST), 4. change in the emission factors (ΔEF), and 5. change in vehicle kilometer travel (ΔVKT), 6. change in per unit vehicle fuel consumption (ΔFC), 7. change in per unit battery production emission (ΔP_{batt}), 8. change in per unit fuel production emission (ΔP_{fuel}), and 9. change in per unit vehicle production emission ($\Delta P_{vehicle}$). Note that ΔEF only represents the contribution from grid emission intensity change since the emission factors of other fuels (gasoline and diesel) are assumed constant. The effect of fleet electrification is embodied in ΔFST, which can be interpreted as a cumulative effect of the change to the share of all BEVs in the fleet (i.e., for use phase emissions) and the change to the share of new BEV sales in the fleet (i.e., for manufacturing emissions). A detailed description of these contributing factors is provided in Table S3.

Each of the contributing factors is computed based on Eq. (2) following the LMDI (Ang, 2004, 2005). Note that in addition to the decomposition on temporal profiles, which are computed for each fleet every year from 2020 to 2050, we also used this approach to decompose the differences in fleet life cycle emissions spatially (cross-country) at given time slices (e.g., from US to China at year 2050) to highlight fleet differences. To verify the consistency of our decomposition scheme, we first model the annual fleet emissions and calculate temporal changes at intervals of 1, 5, and 10 years. We then decompose emissions using Equations (1) and (2) and calculate the aggregated contributions from all decomposed factors as in Equation (2), which also gives the emissions changes at a given time interval. By comparing these two results, we found that the discrepancy at all three temporal intervals is less than 0.5%, likely only due to rounding errors. This minor variance demonstrates the methodology's accuracy for decomposing fleet life cycle emissions. The numerical results are provided in Table S4.

$$
\begin{aligned}
\Delta GHG &= GHG^{t_1} - GHG^{t_0} \\
&= \Delta POP + \Delta VPC + \Delta FST + \Delta EF + \Delta VKT + \Delta FC + \Delta P_{batt} + \Delta P_{fuel} \\
&\quad + \Delta P_{vehicle}
\end{aligned}
$$

$$
\begin{aligned}
&= \sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{POP^{t_1}}{POP^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{VPC^{t_1}}{VPC^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{FST_{s,p}^{t}}{FST_{s,p}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{EF_{s,p}^{t}}{EF_{s,p}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{VKT_{s,p}^{t}}{VKT_{s,p}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{FC_{s,p}^{t}}{FC_{s,p}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{P_{batt_{s,p}}^{t}}{P_{batt_{s,p}}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{P_{fuel_{s,p}}^{t}}{P_{fuel_{s,p}}^{t_0}}\right) + \ldots \\
&\sum_s \sum_p \frac{GHG_{s,p}^{t_1} - GHG_{s,p}^{t_0}}{\ln GHG_{s,p}^{t_1} - \ln GHG_{s,p}^{t_0}} \ln\left(\frac{P_{vehicle_{s,p}}^{t}}{P_{vehicle_{s,p}}^{t_0}}\right)
\end{aligned}
\tag{2}
$$

2.4. Scenario analysis

The life cycle fleet GHG emissions are modeled from 2020 to 2050 based on scenarios of different BEV penetration timelines and a reference scenario of fixed sales shares. For example, the BEV 2035 scenario assumes a linear increase in BEV sales to reach 100% by 2035, and the sales of other vehicle technologies decrease proportional to their projected relative market share. Each of the new vehicle sales scenario is then modeled with a fixed present-day grid or a projected decarbonized electricity grid (Table 2).

These scenarios are selected to investigate: 1) the impact of different electrification timelines on fleet GHG emissions in each country and 2) the sensitivity of fleet GHG emissions to grid carbon intensity in each country for each of the electrification scenarios. Details on the scenario design are provided in the Supplementary Information Fig. S1 depicts the BEV sales in each country for the three vehicle sales scenarios: fixed sales shares (FSS), 100% BEV by 2035 (BEV2035), and 100% BEV by 2045 (BEV2045), Fig. S2 depicts the vehicle ownership rate (vehicles per capita) projections and Fig. S3 shows the annual average grid GHG emission intensity for the fixed and decarbonized grid scenarios in each country.

3. Results and discussion

3.1. US: high-emission fleet with higher benefit from electrification

LDVs in the US are on average more emission-intensive than their counterparts in China and the UK given their higher weight (1850 kg for an average LDV and 1910 kg for an average BEV), greater vehicle kilometers traveled per year (18,100 km), larger BEV batteries (70 kWh in average capacity), and older age (10.2years) resulting in lower average fuel efficiency (Fig. 2). The US possesses a large LDV fleet (over 230 million) with the highest ownership rate (0.7 vehicles/person) among the three countries. Furthermore, the US lags behind in terms of the BEV sales share in 2022 (4.8% as compared to 19.3% in China and 16.6% in the UK). These characteristics highlight the urgent need for the US fleet to decarbonize.

Overall, the US fleet has the largest present-day GHG emissions, but it is expected to gain the highest GHG reduction from electrification (Fig. 3). Compared to the reference (FSS) scenario, BEV2035 reduces 745 $MtCO_2eq$ (65%) in annual emissions for the US fleet by 2050, which is higher than the 515 $MtCO_2eq$ (61%) and 40 $MtCO_2eq$ (56%) for the CN and UK fleets, respectively. From an emission mitigation perspective, we show that fleet electrification can be an effective strategy for all three countries. The modeled BEV2035 policy reduces over 50% of annual life cycle emissions for all three fleets (Fig. 3a).

For cumulative GHG emissions (Fig. 3d) across the study period, electrifying the US fleet by 2035 leads to an emissions reduction of 11.2 $GtCO_2eq$ (30% compared to the reference FSS scenario) which is also significantly higher than the 7.5 $GtCO_2eq$ (27%) obtained for the CN fleet. As a step toward validation, we compared our results with those of

Table 2
Scenarios modeled in this study. Based on combinations of different new vehicle sales shares and grid emission intensities.

Scenario	Grid	Spatial and temporal coverage	Details
Fixed Sales Shares (FSS, the reference scenario)	1) Fixed year-2020 grid or 2) projected decarbonized grid	US, China, UK (2020–2050)	New vehicle sale shares for each powertrain are fixed at the 2022 level.
BEV 2035 (the aggressive electrification scenario)	1) Fixed year-2020 grid or 2) projected decarbonized grid	US, China, UK (2020–2050)	Linear increase of the sales share of BEV until it reaches 100% of all new vehicle sales in 2035.
BEV 2045 (the moderate electrification scenario)	1) Fixed year-2020 grid or 2) projected decarbonized grid	US, China, UK (2020–2050)	Linear increase of the sales share of BEV until it reaches 100% of all new vehicle sales in 2045.

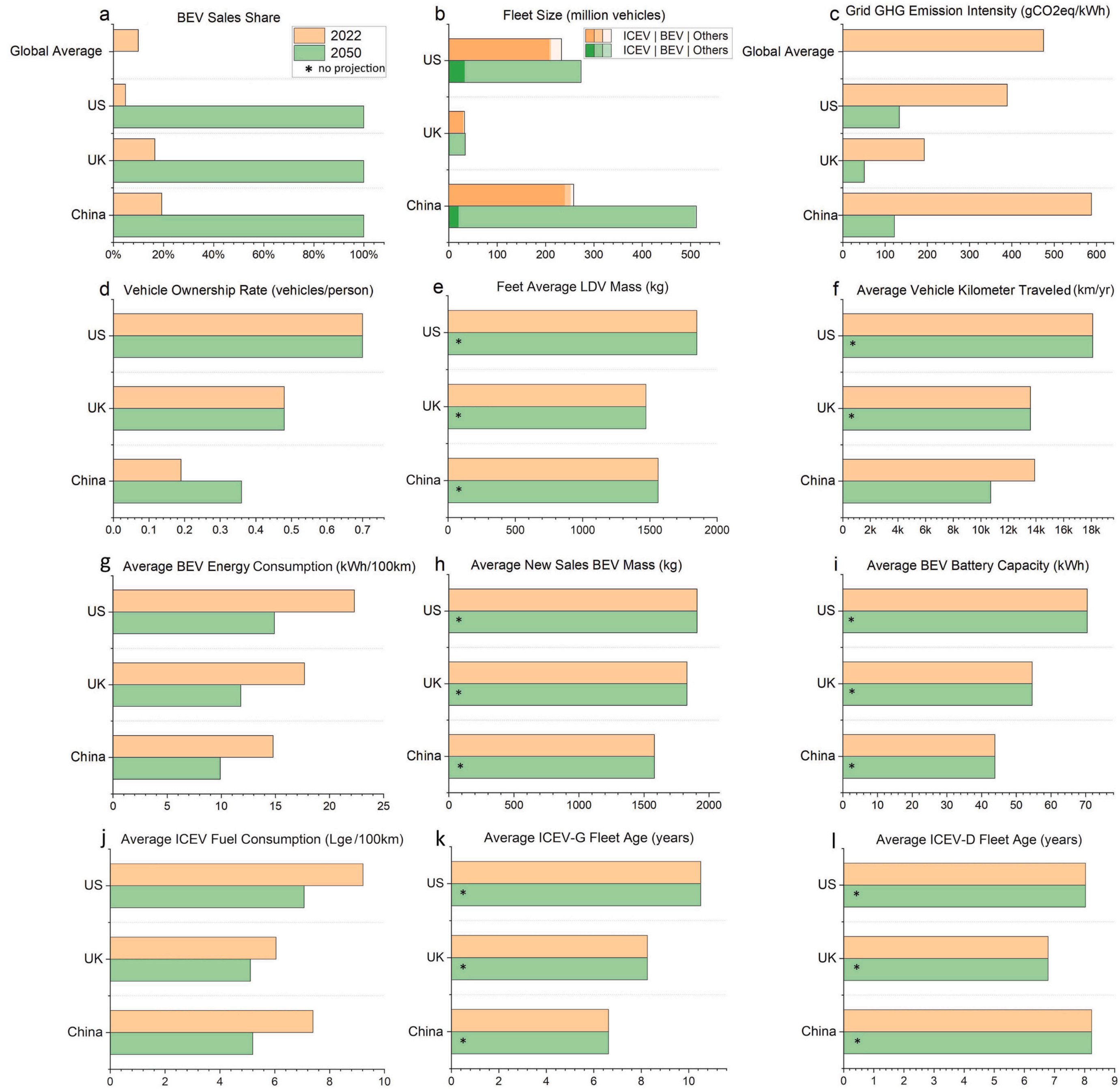

Fig. 2. Cross-country comparisons of fleet and vehicle characteristics for the BEV2035 scenario with projected decarbonized grid.

the U.S. Environmental Protection Agency (EPA, 2022) and Ghandi and Paltsev (2020), which estimated that the tailpipe emissions from US LDV fleet in 2020 were 957 $MtCO_2$ and 1010 $MtCO_2$, respectively. These align well with our modeled result for the vehicle use stage of 940 $MtCO_2$ (a 2%–7% difference, which is within a reasonable range given the different data sources and methods). As the greenhouse effect is more related to cumulative than annual GHG emissions, it highlights the larger projected GHG contributions from the US, and therefore the larger opportunity to reduce its emissions. The successful implementation of the US' fleet electrification will require measures to address infrastructure challenges and spur consumer shift to facilitate growth from its currently low BEV market share (Fig. 2a).

3.2. *China: a doubling fleet size with higher benefits from grid decarbonization*

Chinese ICEVs are on average more energy-efficient (7.4 Lge/100 km) than their US counterparts (9.2 Lge/100 km) and less energy-efficient than their UK counterparts (6.0 Lge/100 km). Chinese BEVs are on average the lightest (1,580 kg) and have the smallest batteries (44 kWh), as a result, they are on average the most energy-efficient among the three countries (Fig. 2g). Additionally, China has the highest present-day BEV market share (19%), which puts the country in a relatively more advanced fleet-electrification transition stage. However, the overall ICEV fleet in China is the youngest (6.6 years on average) among the three countries (Fig. 2k), which could be an obstacle for further EV penetration as these younger ICEV-Gs are less likely to be

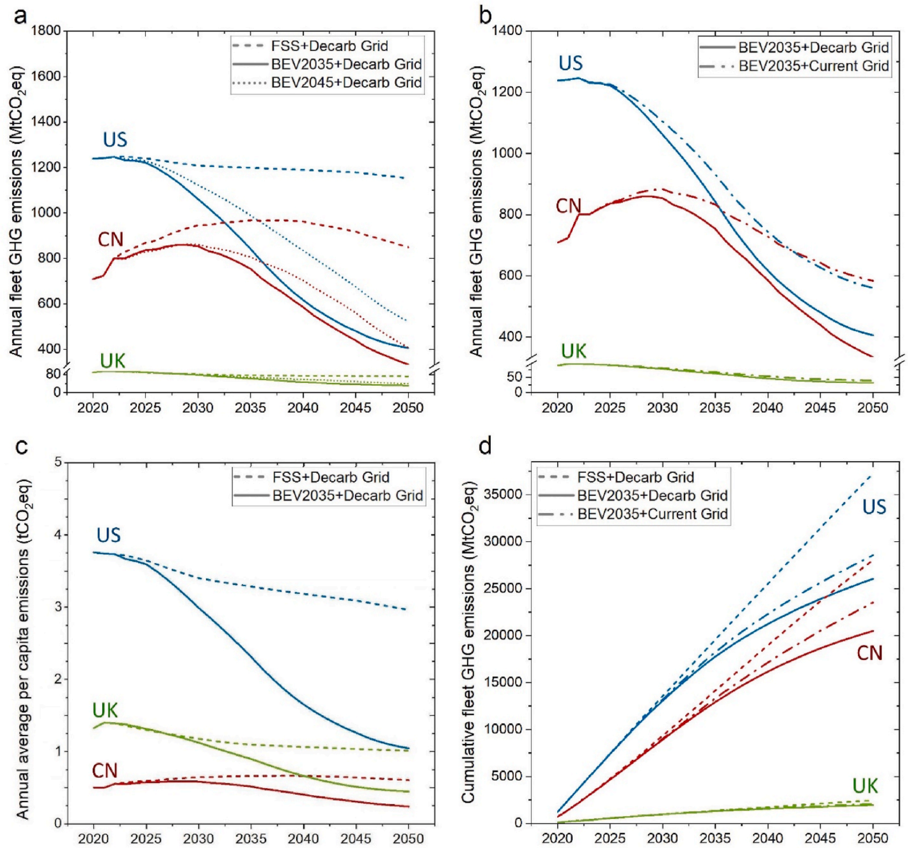

Fig. 3. Cross-country comparisons of fleet life cycle GHG emissions for the modeled scenarios from 2020 to 2050. a). Annual emissions for the fixed-sales-share scenario (FSS) and two electrification timelines (BEV2035, BEV2045) with decarbonized grids. b). Annual emissions reveal the effect of grid carbon intensity (decarbonized versus fixed) on fleet emissions. c). Annual average per capita emissions for three fleets with decarbonized grids. d). Cumulative emissions for the FSS and BEV2035 scenarios.

replaced in the near-term, thus reducing the immediate prospect for new BEV purchases. Note that the fixed-sales-share scenario assumes no change in the sales share for different powertrain technologies but still enables further penetration of BEVs in the on-road stock as the existing vehicles (which currently skew toward ICEV) reach their end-of-life. Further, the scenario includes projected technological advances suggesting a 1% annual improvement in ICEV fuel consumption as detailed in the SI. In China, the expected rise in vehicle ownership is relatively modest and is further moderated by demographic trends (population decline). Taken together, the modest increasing penetration of BEVs, the assumption of continuous fuel consumption improvements, and limited growth in vehicle ownership and associated VKT lead to a peak in annual fleet emissions around 2040 in the FSS scenario (Fig. 3a). Failure to achieve long-term improvements in fuel efficiency or to limit the growth in VKT could overturn this observation.

Comparisons between the fixed present-day grid versus decarbonized grid for the BEV2035 scenario (Fig. 3b and 3d) show that grid decarbonization benefits all three fleets, but it is particularly effective for the CN fleet. The projected decarbonized grid reduces an additional 250 $MtCO_2eq$ (43%) in annual emissions and 3000 $MtCO_2eq$ (13%) in cumulative emissions by 2050 for the CN fleet (compared to BEV2035 with a fixed grid). In contrast, a decarbonized grid would result in a relatively smaller additional reduction of 150 $MtCO_2eq$ annually (27%) and 2500 $MtCO_2eq$ cumulatively (9%), by 2050, for the US fleet, and 8 $MtCO_2eq$ annually (25%) and 140 $MtCO_2eq$ cumulatively (7%), by 2050, for the UK fleet.

Grid decarbonization is more effective for the CN fleet due to three reasons: 1) The present-day grid in China is more carbon intensive (Fig. 2c); 2) The future fleet size in China is projected to double to 520 million by 2050, which is over 80% larger than the projected US LDV fleet size (Fig. 2b), therefore, the effect of grid decarbonization will also be magnified; and 3) China has more ambitious grid decarbonization, with a planned grid intensity decrease from 635 gCO_2eq/kWh in 2022 to 122 gCO_2eq/kWh by 2050 (Fig. 2c). Note that US grid decarbonization is also critical given the size of its projected BEV fleet. For the UK, its present-day grid intensity is already considerably lower and will continue to have a cleaner grid than the other two countries.

3.3. *UK: a smaller fleet with a low-carbon grid*

ICEVs in the UK are on average the lightest (1,470 kg, Fig. 2e) and most energy-efficient among the three countries (Fig. 2j). UK BEVs on average have a moderate weight (1830 kg, Fig. 2h) and a moderate battery size (55 kWh, Fig. 2i), making them more energy-efficient than the BEVs in the US but less energy-efficient than the Chinese BEVs (Fig. 2g). Overall, the UK has several advantages in fleet electrification and decarbonization: it has the cleanest electricity grid among all three countries (193 gCO_2eq/kWh in 2022), which is expected to further decrease to 51 gCO_2eq/kWh by 2050. The UK also has a relatively high present-day BEV sales share (16.6%) and a much smaller fleet size with a slow projected growth (from 32 million in 2022 to 34 million in 2050) that could make the country's fleet electrification less challenging than in China or in the US. Delaying the electrification target date in the UK, from 2035 to 2045, impacts annual emissions by 7 $MtCO_2eq$ (22%) by 2050, which is comparatively smaller than the US and China in absolute terms but similar in relative terms. A similar 10-year electrification delay raises the annual 2050 emissions in the US and China by 29% and 22%, respectively; in absolute terms this translates to an increment in annual emissions of 117 $MtCO_2eq$ and 73 $MtCO_2eq$, respectively, by 2050.

3.4. Per capita emissions: cross-country gaps will shrink with electrification

For fleet-averaged per capita emissions (Fig. 3c), the absolute emission gaps between the three countries will shrink significantly with electrification although the relative gaps between countries are still large. In 2022, the average per capita emissions for the US, CN and UK fleets are 3.7 tCO_2eq, 0.6 tCO_2eq, and 1.4 tCO_2eq, respectively. In 2050 under the BEV2035 scenario, the values are projected to be reduced to 1.0 tCO_2eq, 0.2 tCO_2eq, and 0.4 tCO_2eq, respectively. The US would have the largest decrease in per capita emissions (from 3.7 tCO_2eq to 1.0 tCO_2eq, 73%) with electrification but its vehicles, on average, remain more carbon-intensive than those in China or the UK. Note that the relative gaps between countries remain large even with electrification, which suggests that behavioral changes (e.g., reduced VKT), complementary measures (e.g., smaller vehicles, low carbon fuels) are also needed for countries like the US to further reduce its per capita emissions.

A breakdown of emissions by life cycle stages (Fig. 4a) shows that for an ICEV, fuel consumption dominates the emission difference, being responsible for 45–50 tCO_2eq for an average ICEV in the US, 28–30 tCO_2eq in the UK, and 17–24 tCO_2eq in China. Fuel production emissions are also higher in the US, while the present-day (2022) vehicle materials and manufacture emissions are higher in China (7.7 tCO_2eq versus 5.9tCO_2eq in the US and 4.4 tCO_2eq in the UK). For a BEV, emissions from electricity consumption dominate the differences in 2022 (13 tCO_2eq in the US versus 10 tCO_2eq in China and 3.6 tCO_2eq in the UK), while it is projected to decrease over time due to the planned grid decarbonization (in 2050, the corresponding emissions are 5.3 tCO_2eq, 1.9 tCO_2eq, and 1.2 tCO_2eq for the US, China, and UK, respectively). BEV manufacturing emissions are currently higher in China (9.1 tCO_2eq versus 6.2 tCO_2eq in the US and 5.5 tCO_2eq in the UK) but it is projected to decrease to the same level as in the other two countries by 2050. We note that BEVs are more carbon-intensive to manufacture (mostly due to batteries) in all three countries. For the modeled per vehicle manufacturing emissions, a detailed comparison against other studies is provided in the SI.

Replacing an ICEV with BEV (selling one BEV in place of selling one ICEV) in the US on average avoids 45 tCO_2 of life cycle emissions in 2022 (Fig. 4b) based on BEV2035 with a decarbonized grid, which is significantly higher than a replacement in China (17 tCO_2eq) or in the UK (24 tCO_2eq). This, again, reflects the characteristics of the average ICEV fleet in the US, which, on average, is older, heavier, less fuel-efficient, and tends to travel longer distances annually. While this study has focused on replacing the average ICEV with a BEV, similar trends would likely be observed if the average ICEV is replaced with other modern technologies like PHEV and HEV.

This study assumed a 15-year lifespan (the average value for US ICEVs) for all BEVs and ICEVs due to data availability and consistency, however, a recent study found that the average lifespan of BEVs in China is lower than ICEVs, leading to a higher life cycle CO_2 emission per kilometer (Yu et al., 2022), which represents a limitation to be addressed in future work.

3.5. Decomposition: electrification contributes most for all but other driving factors differ

The LMDI decomposition results are presented in Fig. 5 and a detailed list of values is provided in Table S4. For the US BEV2035 scenario, population growth (*POP*, blue) is the only factor that will drive emissions up, contributing an increase of 150 $MtCO_2eq$ from 2020 to 2050. A change in fleet structure, caused by electrification (*FST*, green), is the dominant factor for emissions reduction, accounting for 75% (758 $MtCO_2eq$) of all emissions reductions from 2020 to 2050. Improvements in fuel consumption (*FC*, grey) and grid emission factor (*EF*, pink) contribute to 15% and 4% of the overall emissions reduction, respectively. Other factors are relatively less significant.

For the CN BEV2035 scenario, growth in vehicle per capita (*VPC*, orange) is the dominant factor that will drive emissions up – by 626 $MtCO_2eq$ from 2020 to 2050. Fleet electrification (*FST*) will be key for emissions reduction, accounting for 50% (512 $MtCO_2eq$) of all emissions reduced from 2020 to 2050. Importantly, a significant factor contributing towards emissions reduction is grid decarbonization (*EF*), accounting for 143$MtCO_2eq$ (14%), followed by improvements in vehicle production emissions (*P_vehicle*), *FC* and *VKT*. Other factors are relatively less significant.

For the UK BEV2035 scenario, population growth (*POP*) will slightly drive emissions up by 4$MtCO_2eq$ from 2020 to 2050, which is small when compared to electrification (*FST*), which reduces emission by 50 $MtCO_2eq$. The improvements in FC and battery production emissions (*P_batt*) reduce emissions by 5 $MtCO_2eq$ and 4 $MtCO_2eq$, respectively. Other factors are relatively less significant.

The cross-country decomposition is a more comprehensive way to highlight fleet differences, which can be used to quantify the required contribution of each factor to match one fleet to another: between the US and CN fleets, the differences in POP and VPC are significant, and moreover, the CN fleet has an advantage in VKT, FC, FST (year 2050), P_fuel and P_batt. Note that although batteries are all assumed to come from China, P_batt is lower in China than in the US due to the latter's bigger battery size per vehicle, averaging about 60% larger in the US than China. Between the CN and UK fleets, the POP difference is the most dominant, and while the difference in VPC is significant in 2020, it becomes less apparent by 2050. Compared to the CN fleet, in 2020, the UK fleet benefits more from its cleaner grid (*EF*) and EV uptake (*FST*), but by 2050, most of the contributing factors are in favor of the CN fleet.

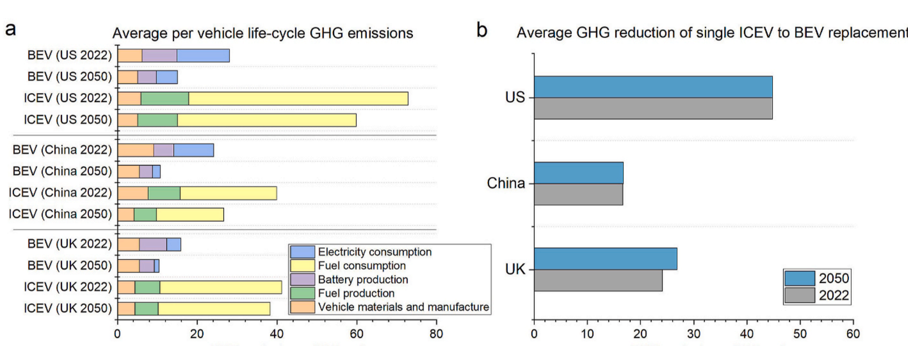

Fig. 4. Cross-country comparisons of a). Average per vehicle life cycle emissions of ICEV versus BEV (assuming a 15-year vehicle lifespan). b). GHG mitigation benefit of single ICEV to BEV replacement based on the fleet-averaged result with decarbonized grid.

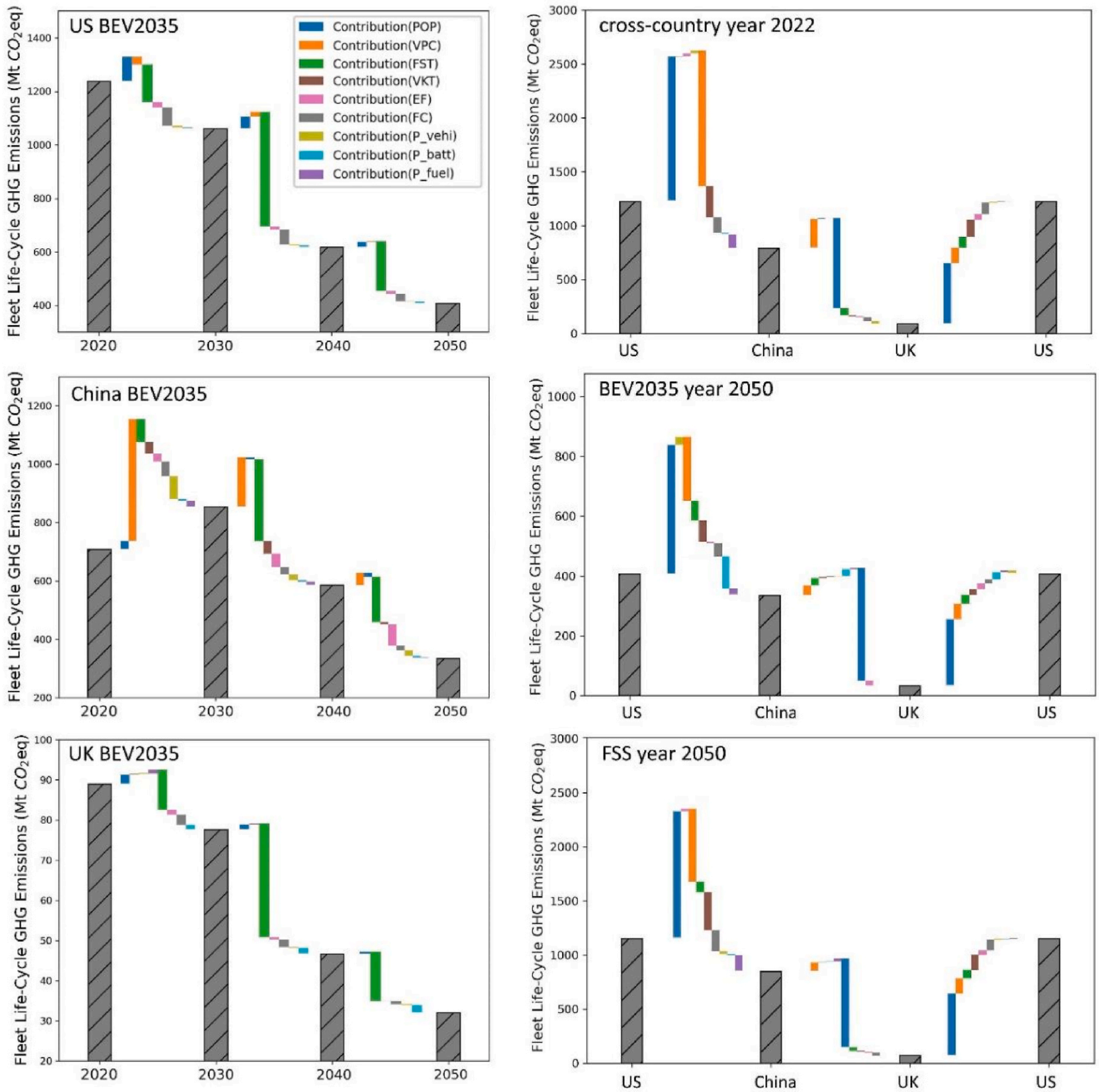

Fig. 5. LMDI decomposition of life cycle emissions for the three fleets. The left panel depicts the temporal decomposition results for each country. The right panel depicts the spatial (cross-country) decomposition results. Grey bashed bars represent the annual fleet total emissions plotted every 10 years. Each smaller bar represents the contribution from the change of one factor, including population (*POP*), vehicle per capita (*VPC*), fleet structure from electrification (*FST*), vehicle kilometer travel (*VKT*), emission factor (*EF*), vehicle fuel consumption (*FC*), per unit vehicle production emission (*P_vehi*), per unit battery production emission (*P_batt*), and per unit fuel production emission (*P_fuel*).

On the other hand, our decomposition analyses also suggest that all these factors are contributing to higher emissions in the US compared to the UK fleet. These comparisons indicate that regardless of the fleet size differences, the CN and UK fleets are less carbon-intensive than the US fleet in all scenarios, where the UK currently has the least carbon intensive fleet.

In summary, compared to other contributing factors, electrification (represented by FST) has the highest impact on fleet GHG emissions reduction for all three fleets, especially from 2030 to 2040 (Fig. 5). Improvement in FC has the second highest contribution to the US and UK fleets, while EF, which represents grid decarbonization has the second highest contribution to the CN fleet, and its significance increases over time as the BEV share grows. Population growth will lead to a moderate emission increase for the US and UK fleets. For China, the rapid rise in vehicle ownership (VPC) will significantly drive emissions higher, which will largely offset the benefits of electrification. This highlights that, while fleet electrification has the potential to significantly reduce GHG emissions in all three countries, there could be other counteracting factors that may diminish its effectiveness. It is also important to note that in this study, the fuel carbon intensity was held as a constant for simplicity, and therefore the use of lower-carbon fuels could be another complementary factor to reduce fleet emissions, which should be further investigated.

3.6. Batteries: highest GHG mitigation benefits in the US fleet

Deployments of the world's limited battery capacity in different countries could achieve different GHG reduction benefits. Based on the modeling results of the BEV2035 scenario, the estimated cumulative BEV battery demand from 2020 to 2050 would be 25 TWh, 31 TWh, and 3.4 TWh for the US, China and the UK, respectively. We compare the average GHG reduction per kWh of battery for each fleet based on the BEV2035 scenario with decarbonized grid (Fig. 6a). Results are presented on both, vehicle life cycle basis (i.e., emission reductions per kWh

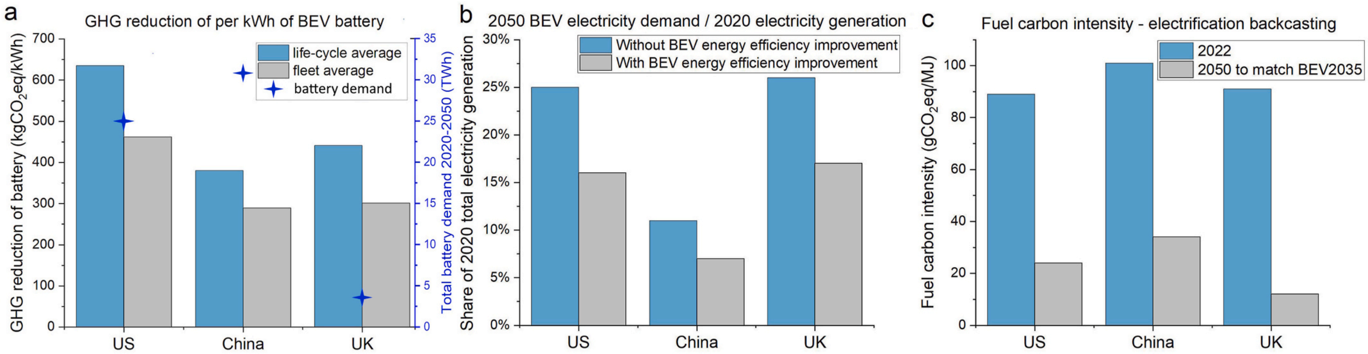

Fig. 6. Cross-country comparisons of a). average life cycle GHG reduction per kWh of BEV battery based on the BEV2035 with decarbonized grid. Total battery demand from 2020 to 2050 for each fleet is indicated by the secondary axis. b). Electricity demand of the projected 2050 BEV fleet in relative to the total electricity generation in 2020. c). Fuel carbon intensity back-casting models the required reduction of fuel carbon intensity for each country in 2050 to match the same emissions mitigation effect of the 2035BEV scenario.

from converting an ICEV to a BEV, over a 15-year lifespan of the vehicle from 2020 to 2035) and on a fleet basis (i.e., total GHG reduction from 2020 to 2050 in the BEV2035 scenario relative to FSS, normalized against total kWh of battery deployed during that time). On a fleet level, between 2020 and 2050, every kWh of BEV battery in the US could lead to an average GHG reduction of about 460 gCO_2eq, which is 59% more than in China (290 gCO_2eq/kWh) and 53% more than the UK (300 gCO_2eq/kWh). This would suggest that BEV batteries could enable greater GHG reduction in the US than in China or the UK, consistent with the discussions in the preceding section.

3.7. Electricity demand: US and UK grids need to expand by a higher percentage

Fleet electrification raises the demand for electricity. Our estimates indicate that for the US, the on-road electricity demand of BEV fleet in 2050 is equivalent to 16%–25% of the country's 2020 total electricity generation depending on whether BEV energy efficiency improvement is accounted for (Fig. 6b). For the UK, it is 17%–26%, and for China it is significantly lower at 7%–11% due to China's high electricity generation capacity to support its large population and the manufacturing sector. This highlights the challenge of electrification on the power sector, especially for the US and the UK, as both countries would need to expand their annual electricity generation by about 20% to support a large BEV uptake within the fleet in the future.

3.8. Low-carbon fuel opportunities: different carbon intensity targets across countries

To provide insights to guide developments of low-carbon fuels (e.g., efuels, biofuels), we estimated the carbon intensity reduction that is required of conventional fuels for the fleet to match the annual GHG emissions in each country under a BEV2035 scenario (Fig. 6c). Here, we show that, by 2050, the life cycle fuel carbon intensity would need to decrease by 65 gCO_2eq/MJ (from 89 to 24 gCO_2eq/MJ), 67 gCO_2eq/MJ (from 101 to 34 gCO_2eq/MJ), and 79 gCO_2eq/MJ (from 91 to 12 gCO_2eq/MJ) for the US, China, and UK, respectively. The required reduction in fuel carbon intensity is lower in China and the US, suggesting less stringent carbon intensity targets for alternative fuels to match the benefits from BEVs in China and the US than the UK.

These levels of carbon intensity reductions translate to a fuel life-cycle GHG savings of 73%, 66%, and 87% for the US, China, and the UK respectively. To put this into context, the EU's renewable energy directives currently already require fuels of non-biological origin to achieve at least 70% GHG reduction over conventional fuels. On the other hand, the certified fuel pathways under California's Air Resource Board (CARB)'s low carbon fuel standard (LCFS) has a carbon intensity range of 7–77 gCO_2eq/MJ for ethanol and 21 to 63 gCO_2eq/MJ for renewable gasoline (California Air Resource Board, 2023b).

By gradually ramping up production and increasing the blend concentration of low-carbon fuels in conventional gasoline, it may be possible to address some challenges associated with fleet electrification. While there are concerns on how much low-carbon fuels would be available and their impacts on costs and other environmental impacts, the co-deployment of a multi-prong decarbonization strategy, including vehicle electrification, low-carbon fuels and modal shift, could prove to be beneficial in managing some of the capacity and resource constraints arising from a reliance on a single decarbonization technology.

3.9. Limitations and future work

We acknowledge that limitations exist in the models but given the scope of this study, it is not feasible to cover all identified aspects. Here we list a number of key aspects that are potential topics to explore in future research:

The models in this work all assume fleet average behavior in each country, and do not distinguish among a range of local (sub-national) conditions, such as urban versus rural fleets.

The models use country-level projections for vehicle travel demand, which implicitly capture what each country believes to be their respective baseline/reference scenarios for technology and mode share projections. Nevertheless, there are large uncertainties associated with these projections and future work should explore the impacts of potential modal shifts and the introduction of new technologies or infrastructure.

The models' long-term horizon (2020–2050) introduces inherent uncertainties, particularly in how the changing regulatory landscape and global events might influence the evolution of the fleet model. Regulatory shifts, such as enhanced emissions standards, EV incentives, and renewable energy mandates, could accelerate the adoption of electric vehicles and the decarbonization of the power grid, thereby impacting fleet composition and emissions. Conversely, global events like economic downturns or technological breakthroughs might hinder or propel fleet electrification in unpredictable ways. While the model provides a valuable framework for understanding potential pathways to decarbonization, its projections must be viewed as scenarios that could be substantially altered by future changes in policy and global circumstances, underscoring the need for flexible and adaptive policymaking. Further studies should explore a wider array of factors and uncertainties, including technological advancements, the impact of global events, regulatory shifts, and changes in consumer behavior to refine projections, adapt strategies to emerging challenges, and guide more effective decarbonization policies.

The choice of the UK in this study is not intended to represent Europe as a whole, especially considering the UK's departure from the European Union (EU) and its distinct regulatory and policy landscape. Notably, the UK's target to end the sale of new petrol and diesel vehicles by 2035 aligns with our modeled scenario and distinguishes its approach from that of some EU countries. Future studies are planned to cover other geographies, aiming to provide a more comprehensive view of the electrification potential and challenges across different regulatory and market contexts.

The fleet emissions decomposition analysis only estimates emissions from vehicle dismantling and does not include complete end-of-life emissions. This results from data limitations and that end-of-life emissions estimates are highly dependent on the methodology and allocation assumptions employed (Nordelöf et al., 2019; Accardo et al., 2023). Cross-country comparison of vehicle end-of-life scenarios is left as an area for future work.

Our model uses a linear increase projection of BEVs reaching 100% of all new vehicle sales by 2035 due to limitations in available data and the need for simplicity and consistency across the three models. A linear model serves as a straightforward baseline when data are limited. For future work, a more realistic deployment projection would be based on a non-linear model such as a Bass, Logistic or Gompertz curve (Kumar et al., 2022). Adopting one of these multi-parameter distributions could somewhat shift the exact timing of BEV adoption and resulting emissions, but would require additional assumptions and increased model complexity, which would not necessarily improve model fidelity for the present study.

Another limitation of the study is that while FLAME-US accounts for the annual mileage change as a function of vehicle age, FLAME-UK and FLAME-CN currently do not have this parameter due to lack of data availability. This limitation should be addressed in future work.

Our study models a present-day battery technologies mix reflecting realistic market shares of LFP, LMO, NCM/NMC, and other battery chemistries (detailed in the SI). Different battery chemistries can significantly impact manufacturing emissions but these emissions are a small portion of cumulative fleet life cycle GHG emissions in our scenarios. Previous research suggests the lifecycle emissions differences among battery types may not be that large, especially when factoring in possible weight increases that may offset lower manufacturing emissions from certain chemistries like LFP (Tarabay et al., 2023). Future work could investigate scenarios with different battery technologies and the impacts of the evolving battery technology landscape.

4. Conclusions and policy implications

4.1. Common findings for all three countries

Electricity demand: All three countries need to consider the infrastructure and material challenges associated with an ambitious fleet electrification policy. Demand for electricity from the LDV fleets is expected to grow significantly by 2050 (Fig. 6b). Policies should focus on expanding low-carbon electricity generation capacity, improving grid flexibility and stability with new technologies in energy storage and vehicle-to-grid systems as well as investing in abatement technologies for its existing power generation fleet while rapidly increasing renewable energy production (Yuan et al., 2023). Other complementary measures, beyond electrification, are also needed to drive the fleets towards an effective and timely decarbonization.

Critical materials: The success of electrifying the fleets will highly rely on sufficient critical minerals supply, which may require the countries to take some complementary solutions alongside the electrification. A recent study (Tarabay et al., 2023) showed that the EV sector in the US alone could create substantial demand for lithium, cobalt, and nickel, surpassing 2020 global production levels for these metals. Possible solutions to this issue could include adopting batteries with a lithium iron phosphate dominant cathode and adopting PHEVs, both of which reduce demand for critical minerals. Critical metal demand for fleet electrification could become an issue in ambitious scenarios like achieving 100% EV penetration globally, given current estimates of critical metal reserves (Tarabay et al., 2023). However, China's current overcapacity in battery manufacturing (Shao and Jin, 2020) and its established supply chains suggest that supply bottlenecks are more likely to occur in specific geographies, potentially affecting industrial development. Aspects such as global supply chain dynamics and technological advancements in recycling and alternative materials could mitigate some concerns over critical metal availability.

Low-carbon fuels and other strategies: The complementary use of sustainable, low-carbon fuels could accelerate decarbonization of ICEVs in the fleet. Our preliminary analysis estimates that the fuel carbon intensity would have to be reduced by 73%, 66%, and 87% by 2050 for the US, China, and the UK, respectively, in order to achieve similar annual GHG emission level as the BEV2035 scenario. It is important to recognize other strategies to accelerate decarbonization beyond the use of sustainable, low-carbon fuels, which may face availability limitations. Strategies such as vehicle downsizing, along with policies aimed at reducing vehicle ownership, provide opportunities for decarbonization. This is exemplified by policies implemented in China, which focus on maintaining lower levels of vehicle ownership and enhancing alternatives to car travel, including investments in public transport. Acknowledging these solutions underscores the multifaceted approach needed to substantially decarbonize the transport sector. However, some assessments (ICCT, 2023; IEA, 2024b) argue that, given the high costs of producing liquid hydrocarbons at scale, it would be more appropriate to prioritize e-fuel and biofuel production for sectors like medium-/long-distance shipping and aviation where there are more limited alternatives.

LCA in policymaking: LCA is a useful tool in decarbonization policymaking (Xue et al., 2023). Our life cycle modeling and comparisons highlight that holistic policy packages that are based on well-to-wheels life cycle assessment will be essential for decarbonizing the LDV fleets. While adopting a life cycle perspective is decidedly helpful for guiding policies and avoiding burden shifting across the supply chain, the policy itself need not be explicitly LCA-based. An alternative policy framework that targets different regulated entities with specific regulations can effectively address various stages of the automotive supply chain. This approach allows for tailored strategies to decarbonize each component, such as low-carbon steel for vehicle construction, a transition to lower emitting travel modes and more efficient powertrains, clean energy policies for power and fuel production, rather than relying solely on one LCA-based regulation. Nevertheless, LCA remains an important tool for informing priority emission hotspots and for evaluating outcomes that are likely to result from attempts to create a comprehensive patchwork of component or sector-specific strategies.

4.2. US: facilitate electrification, promote fleet turnover and behavioral changes

Priorities: Facilitating vehicle electrification is a priority for the US fleet. This is considering the substantial lag in BEV market share compared to other countries (Fig. 2a), and the fact that the US actually stands to gain larger GHG reduction than the UK and China from electrification, at the fleet level, per capita level and battery-level (Figs. 3, 4 and 6a). To some extent, policies are already moving in this direction, as demonstrated by state-level policies such as the zero emission vehicle mandates adopted by California along with several other states (California Air Resources Board, 2022, 2023a), and EPA's recently proposed LDV pollution regulations (EPA, 2023b), which include more ambitious standards for GHG and air pollutant emissions from LDVs starting with model year 2027. These new regulations encourage the adoption of EVs in the US to significantly reduce GHG emissions.

Opportunities: The cross-country benchmarking of per capita and per vehicle emissions (Figs. 3c and 4a) indicates that the US fleet has significant potential for further decarbonization beyond electrification efforts. And the decomposition analysis reveals that vehicle energy efficiency improvement is another key contributing factor to reduce US fleet emissions (Fig. 5). To address this, policies could revolve around encouraging behavioral changes, such as opting for smaller vehicles, reducing mileage traveled, and decreasing the number of vehicles owned per household.

US fleet GHG emissions can be reduced by accelerating vehicle turnover, albeit at a high cost and only if there is a high new sales share of lower emitting vehicles (e.g., EVs) (Striepe et al., 2024). US households have been holding onto their vehicles for longer durations since 2009 as evidenced by surveys on household vehicle travel (U.S. Energy Information Administration, 2018; National Transportation Statistics, 2023). Our comparison shows that 20-year-old vehicles in the US have an average survival rate of 24%, while in China and the UK, the rate is only 7% and 6%, respectively (Fig. 7a). This trend contributes to an overall ageing fleet but could also be an opportunity for the US policies to target old vehicles by implementing additional incentives, such as tax credits, that encourage the replacement of old ICEVs.

Challenges: Other challenges center around behavioral changes. As US households have been used to fuel-intensive vehicles and less public transport, policies targeting lifestyle changes could require substantial incentives to be effective. Improving fuel consumption of the dominant gasoline fleet, downsizing the fleet, and increasing the share of ethanol in blends could also be complementary solutions to reduce GHG emissions from the US LDV fleet (Alzaghrini et al., 2024; Soares et al., 2022). However, we note that a high degree of variability exists in current estimates and methodologies for LCA of GHG emissions intensity of ethanol and other biofuels, reflecting the complexity and diversity of the factors involved (Jeswani et al., 2020).

4.3. China: decarbonize grid, limit fleet growth and reduce manufacturing emissions

Priorities: Prioritizing grid decarbonization emerges as a paramount concern for China. Our findings indicate that, in terms of emission mitigation, grid decarbonization yields greater effectiveness for the Chinese fleet in comparison to the other two countries (Fig. 3b). This observation aligns with the fact that China's present-day grid emission intensity is considerably higher and fleet size is growing faster. A low-carbon grid will also greatly reduce China's vehicle manufacturing emissions. Vehicle manufacturing is on average more carbon-intensive in China compared to the US and the UK (Fig. 4a) mostly due to China's power-intensive vehicle manufacture and carbon-intensive electricity generation (Hao et al., 2017). With the country's ambitious grid decarbonization plan, the unit BEV manufacture emissions in China would decrease by 40% (Fig. 4a), which again highlights the critical need for grid decarbonization in China.

Policies should also target the demand side to limit the fleet growth in China. The soaring vehicle ownership rate in China is the single largest contributor to fleet emissions increase over the next two decades as indicated by the decomposition analysis (Fig. 5). The decomposition reveals that lowering VKT is another key factor to further reduce fleet emissions besides electrification and grid decarbonization in China (Fig. 5). Therefore, the policy package could also promote public transport or vehicle-sharing to reduce vehicle ownership and usage.

Opportunities: As one of the world's largest and fastest-growing car markets in the world, China is moving fast on the path to an electrified fleet. In 2022, new energy vehicle (mostly EVs) sales in China reached 6.8 million units based on the China Association of Automobile Manufacturers, which accounts for about 60% of global light-duty EV market (IEA, 2023). This is attributed to the country's much larger first-time vehicle buyers group compared to the other two countries (Fig. 7b), which presents an opportunity for EV policies. With a substantial pool of potential first-time vehicle buyers, the favorable market conditions and incentives in China can create a conducive environment for increased EV adoption.

China has the highest present-day fleet electrification rate among the three countries (Fig. 2a), and the average weight and battery size of Chinese BEVs are comparatively lower than those in the US and the UK (Fig. 2). While this may result in higher energy efficiency for Chinese BEVs, it also suggests potential benefits in terms of reduced material and energy requirements for manufacturing. This can contribute to lower life cycle emissions and faster production ramp-up.

Challenges: China's rapidly growing BEV fleet is shifting heavy burdens from transportation to the power sector. This transition poses a significant test for China as it must rapidly expand its grid capability while simultaneously working towards grid decarbonization. The significant regional differences in electricity generation capacity and grid carbon intensity across the country is another potential issue in maximizing the environmental benefits of EVs in China (Huo et al., 2015). Addressing this challenge requires a comprehensive approach that focuses on accommodating the increased electricity needs while concurrently reducing the carbon footprint of the power sector.

The uncertainty associated with future car ownership level is relatively large in China, and therefore SI section 1 includes a sensitivity analysis around four ownership scenarios, which predict 0.18 (fixed), 0.37 (projected), 0.48 (UK level), 0.7 (US level) vehicles per person by 2050 (Fig. S2b). The comparison highlights the critical role of fleet electrification: the annual difference in emissions between the best-case scenario (fixed 2022 ownership) and the worst-case (grows to US level) scenario by 2050 is 129 $MtCO_2eq$ for an electrified fleet (BEV2035), while the difference in the ICEV-dominant (FSS) scenario (1035 $MtCO_2eq$) is seven times higher. Importantly, though, higher ownership rates would further challenge the ability of the electric grid to support the required demand and maintain decarbonization plans, and so avoiding large increases in vehicle ownership remains beneficial. Recent

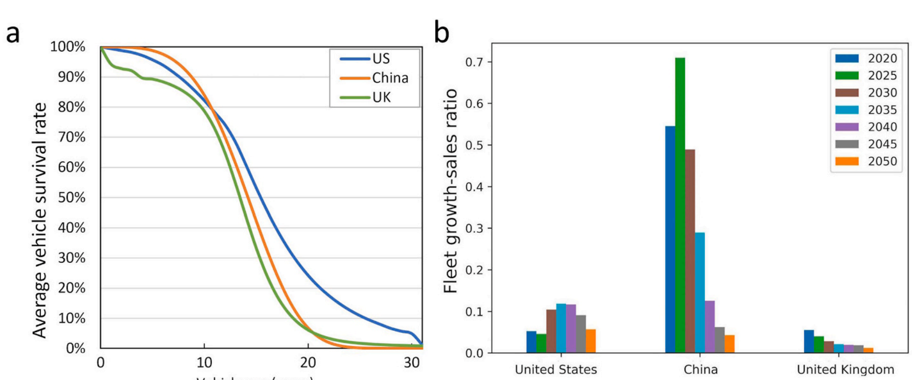

Fig. 7. Cross-country comparison of a). Average vehicle survival rates as a function of vehicle age suggest that US households are holding onto their vehicles for longer durations. b) Fleet growth-to-sales ratio indicates that China has a much larger first-time vehicle buyer group.

studies (Li et al., 2019) identified this challenge but also suggest that car ownership is unlikely to surpass 0.4 vehicles per person in China, a revision from earlier estimates of 0.5 due to the economic slowdown, aging population and high urban population density. For densely populated coastal regions and cities, policies aiming at promoting public transportation and shared mobility are outlined in China's 14th Five-Year Plan for Modern Comprehensive Transportation System Development to limit car ownership (Hepburn et al., 2021; Ibold et al., 2022).

Another challenge in China's LDV decarbonization efforts lies in the age profile of its ICEV fleet. The overall youthfulness of the fleet (Fig. 2k) poses an obstacle to EV penetration as these younger ICEVs are less likely to have high mileage and therefore have a lower immediate need for replacement.

4.4. UK: encourage electrification and expand electricity generation capacity

Priority: Electrifying the fleet and expanding electricity generation capacity should be the priorities for the UK. Electrification is an effective way to reduce GHG emissions for the UK fleet (Figs. 3 and 5) taking advantage of its low-carbon grid. On the other hand, the country would need an additional 17%–26% of electricity to support its future BEV fleet, this percentage is much higher than China, therefore, potentially posing a larger relative challenge in expanding electricity generation.

Opportunities: The UK's present-day high BEV sales share (Fig. 2a) and low-carbon grid (Fig. 2c) provide a favorable starting point for its transition towards a decarbonized transportation system. Policies in the UK have committed to end the sale of gasoline and diesel vehicles by 2035, showcasing the government's ambition to accelerate the transition. However, this is a delay from the initial 2030 electrification target, which suggests the need to balance various conflicting priorities.

Challenges: Diesel vehicles have a higher share in the UK and emit more GHG than ICEV-Gs over lifetimes given that their average VKT is about 50% higher than ICEV-Gs in the UK. This is not necessarily causal; it is more likely that drivers who expect to drive with high annual VKT preferentially purchase diesel vehicles. Nevertheless, this same conjecture suggests the ICEV-D market may benefit strongly from electrification. The ICEV-Ds in the UK are also on average 1.5 years younger than the ICEV-Gs, meaning they are likely to have a longer remaining lifespan, which prolongs their impact on carbon emissions and local air quality. Policymakers may need to provide additional initiatives to encourage the replacement of diesel vehicles with EVs, such as tax credits.

In conclusion, this study employs country-specific LCA models and a novel index decomposition analysis to identify the priorities, challenges, and opportunities associated with fleet decarbonization through electrification in the US, China, and the UK from 2020 to 2050. We highlight the value of cross-country comparisons in benchmarking fleet performance and highlighting unique drivers of emissions both today and over time in different geographies. We provide valuable policy priorities for a more effective road transport decarbonization. This, however, has to be balanced against the challenges that are unique to each country based on their existing fleet characteristics, infrastructure readiness, and socioeconomic profiles, where a disorderly mandate could risk exacerbating many of the challenges typically associated with electrifying a fleet.

CRediT authorship contribution statement

Da Huo: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ben Davies:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Jianxin Li:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Nadine Alzaghrini:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Xin Sun:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Fanran Meng:** Writing – review & editing, Methodology, Conceptualization. **Amir F.N. Abdul-Manan:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Jon McKechnie:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **I. Daniel Posen:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Heather L. MacLean:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Heather L. MacLean reports financial support was provided by Saudi Aramco Technologies Company. D Huo, B Davies, J Li, N Alzaghrini, X Sun, F Meng, J McKechnie, ID Posen reports financial support was provided by Saudi Aramco Technologies Company. Amir F N Abdul-Manan reports a relationship with Saudi Aramco Technologies Company that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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