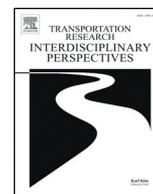




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## UK and China: Will electric vehicle integration meet Paris Agreement Targets?

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### ABSTRACT

It is widely accepted that the true environmental benefit of electric vehicles (EVs) is dependent upon non-tailpipe emissions from fuel/energy production. Through a comparison of EV and conventionally fuelled vehicle (CFVs) tailpipe emissions in China and the UK, considering their different EV integration plans, were projected between 2017 and 2050.

For this analysis, three scenarios were modelled for private vehicles using 'two degree' scenario data for electricity generation: (1) 100% CFVs; (2) 100% EVs; and (3A) 50:50 mix of CFVs and EVs integrated in 2030; and (3B) 50:50 mix integrated in 2040. Results indicated that between 2017 and 2050 for (1) emissions decreased by 56% in China and 91% in the UK, accounting for technological improvements, with emissions per vehicle decreasing by 89% and 24% respectively. Under (2) emissions decreased by 55% in China and by 92% in the UK and decreased by 88% in China and 88% in the UK per vehicle. Under (3) emissions increased by 10% in China and decreased by 43% in the UK, with emissions per vehicle decreasing by 70% and 95% respectively.

Results demonstrate EV deployment is related to economic status of the country, so decarbonisation of the energy sector should be targeted. By transitioning towards EVs in 2030 or 2040 as opposed to 2050, both countries are more likely to meet emission goals. Therefore, policymakers should focus on introducing policy which combines carbon taxes, non-fossil fuels and energy efficiency with any financial profits reinvested to subsidise construction of renewable energy infrastructure.

### 1. Introduction

Worldwide sales of electric vehicles (EVs) have been increasing rapidly over the past decade, a trend which has been mainly driven by policies and incentives, cost reduction and more stringent carbon dioxide (CO<sub>2</sub>) targets for cars (Pagani et al., 2019). China has become an early adopter of EV integration, leading EV production and associated charging infrastructure. This has been achieved through a 'leapfrogging' approach (Gupta et al., 2020) which has been likely influenced by the need to address societal and economic costs from pollution produced from conventionally fuelled vehicles (CFVs). Alternatively, the UK has taken a 'phasing out' approach banning the sale of all new CFVs (and vans and hybrid vehicles) from 2035 onwards allowing low emission transport to be 'phased in' to the transport network. Both countries have begun integrating EVs into their respective transport networks to reduce transport emissions, as part of their commitment to the 2015 Paris Agreement. The aim of this paper is to address the relative merits of China's 'leapfrogging' approach and the UK's

'phasing out' approach by projecting the greenhouse gas (GHG) emissions from three different CFV and EV integration scenarios for private vehicles between 2017 and 2050: (1) 100% CFVs; (2) 100% EVs; and (3A) 100% CFVs between 2020 and 2034 with 50% EVs from 2035 until 2050; and (3B) 100% CFVs between 2020 and 2024 with 50% EVs from 2035 until 2050. By making these projections, relevant recommendations for policymakers, projecting future trends of energy demand and GHG emissions for CFVs and EVs in China and the UK will be necessary to meet their emission reduction objectives.

As part of both China and the UK's commitment to the Paris Agreement, both countries have set up independent emission reduction targets from the leading GHG emitting sectors. China aims to achieve peak GHG emissions by 2030, or sooner, with the Chinese Government focusing on energy conservation and CO<sub>2</sub> emission reductions (Wang et al., 2017). In contrast, the UK aims for net zero emissions by 2050, setting specific targets to increase renewable electricity generation within their energy mix. Focus needs to be placed on transport as this remains the leading emitter of GHG emissions

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within both countries. Over the past several decades, both China and the UK's transport networks have become dominated by conventionally fuelled road transport, particularly for private travel, generating substantial levels of CO<sub>2</sub> emissions through significant energy consumption (DfT, 2019; Lu et al., 2020). This current transport mix has left both countries struggling to meet their emission reduction targets with substantial adjustments needed. Since 2008, China has been the world's largest vehicle producer and consumer with road transport representing ~85% of the transport sector's GHG emissions and energy consumption (Peng et al., 2018a; Wang et al., 2017). Without any significant changes in China's road transport, oil consumption is expected to increase annually by 6% and could reach up to 363 million tonnes in 2030, the equivalent of 1890 MtCO<sub>2e</sub> by 2030 if no new energy conservation policies are implemented (Hofmann et al., 2016; Meng et al., 2017). This increase in emission levels is due to the fuel type used as well as the rapid increase in personal vehicle ownership with 146.4 million vehicles in use in 2019, an increase of 11.9 million since 2018 (National Bureau of Statistics of China, 2020). Comparably, in the UK, road transport is the only sector where emissions have continued to grow, increasing by 6% to ~118 MtCO<sub>2e</sub> by 2017, the equivalent of 21% of the UK's total GHG emissions (ONS, 2019). However, the UK has seen a decrease in the overall number of personal vehicles by 5% (down to ~2.9 million vehicles in 2018), however vehicle size has been increasing with the popularity of new SUVs increasing, resulting in an increase in road transport emissions (Brand et al., 2020).

One solution to meet these targets has been the introduction of EVs as they are considered 'zero emission' at their point of use, but their true environmental impact is dependent on non-tailpipe emissions from fuel/energy production (Canals Casals et al., 2016; Driscoll et al., 2013; Morrissey et al., 2016). However, there are still environmental controversies surrounding EVs as the reduction of emissions from CFVs may be followed by an increase in emissions from the power sector (Teixeira and Sodr , 2018). Therefore, additional low carbon electricity generation from renewables will need to be combined with the modal shift towards EVs to ensure emissions are reduced. However, this transition towards low carbon energy will bring new challenges that need to be addressed as the electric load to charge EVs will require new generation capacity and considerable network reinforcements (Calvillo and Turner, 2020).

As highlighted above, the true impact of EVs is dependent on energy generation in both countries which remains one of the highest emitting GHG sectors. Between 2012 and 2016, China's CO<sub>2</sub> emissions from electricity generation increased by 264%, with thermal power generation accounting for 75% of this increase (Zhao et al., 2020). However in 2016, the average efficiency of thermal power generation in China was 38.1% higher than the OEDC and the USA average, so this has moderated this increase in emissions (Wiatros-Motyka, 2016). Within the same time frame, the UK saw a decrease in emissions of 17% from 196 MtCO<sub>2</sub> to 162 MtCO<sub>2</sub> within the energy supply. This decrease is due to the UK transitioning away from a fossil fuel based energy supply towards nuclear and renewable energy generation (BEIS, 2019a). However, decarbonisation of energy generation may lead to some problems in developing countries. Energy security, which is defined by the International Energy Agency (IEA) as an 'adequate, affordable and reliable supply of energy' (IEA, 2004) could result in several challenges for China, such as the balance between supply and demand, although this is widening and depends on the volatility of international crude oil prices (Rout et al., 2011). As transport has become the largest driver of China's oil demand and a major consumer and importer of oils, shifting towards EVs may allow more centralized energy generation and reduction in oil imports. This is not the case for oil exporting countries like the UK who have already begun to diversify their electricity generation mix and are becoming less reliant on fossil fuels. To meet the energy demand of EVs, both countries will need to increase the level of electricity generated.

Due to the role and influence transport and electricity generation can have on both countries' Paris Agreement objectives, projecting emissions has become an important topic in research, business and policy making. Through a case study comparison between a developing and a developed country, i.e., China and UK, respectively, a greater understanding of how

the energy sector needs to be developed and adjusted to encourage EVs was established. This paper addresses the relative merits of China's 'leap-frogging' approach and the UK's 'phasing out' towards successfully developing clean, energy efficient and economically viable electricity sources for EVs.

## 2. Literature review

### 2.1. China's emissions and electricity generation

Due to rapid economic growth, China has become the world's largest energy consumer and CO<sub>2</sub> emitting country with the energy sector playing a dominant role in releasing GHG emissions (Geng et al., 2013; Yuan and Zhao, 2016). China's future energy choices will play a huge role in determining global trends due to the scale of its energy deployment. To reduce emissions, China has set an ambitious policy target of reducing gross domestic product (GDP) carbon intensity in 2020 by between 40 and 45% based on 2005 levels (Geng et al., 2013; Yuan and Zhao, 2016), with a further target to reduce intensity by between 60 and 65% in 2030 compared with 2005 has also been set (Xu et al., 2017). To meet these targets, each province in China has set more specific and area specific aims and targets within the time frame (Dhakal, 2009; Geng et al., 2013; Wang et al., 2012). However, these targets will be dependent upon many factors including the use of advanced technology and structural policy changes.

However, the geographical and spatial distribution of electricity resources in China remains unbalanced. Although renewable energy costs are decreasing, the cost of electricity generation and renewable energy installation can hinder development. In recent years, growth in renewables has been driven by government-supported programmes through subsidies, tax credits and other incentives (Bhattacharya et al., 2016). This has benefited western China, which has rich energy resources of wind and solar energy, with installation rates showing a steep increase in recent years. However, western China remains economically underdeveloped with limited electricity consumption, so some western areas have overcapacity issues. In contrast, the east and south of China remain relatively developed but the electricity supply is often affected by shortages of resources. This needs to be considered when analysing future energy placements to ensure a strong energy connection with minimal distribution losses.

Table 1 highlights the current and projected electricity generation mix for China based on a scenario where the 2 °C Paris Agreement target is met (Gota et al., 2018). Energy generation mix for China was based on China National Renewable Energy Centre (2015). Although it has been debated in the literature, this increase in energy consumption is both a consequence and driver of growth, with several studies highlighting interdependence between electricity consumption and economic growth within different regions of China (Ayres et al., 2003; Gillingham et al., 2013; Hu and Cheng, 2017). Therefore, as China continues to develop, energy generation will rise, however it is expected that this will peak in 2030.

A potential issue China faces is energy security, which is currently being addressed by the Chinese Government through increased diversification of

**Table 1**  
The electricity generation mix in China in 2015 and the projected mix in 2050 as a percentage and ratio of total (Source: China National Renewable Energy Centre, 2015).

	China (2015) (TWh) (%)	China (2050) (TWh) (%)
Coal	4223 (68.8)	1038 (7.3)
Oil	2 (<0.0)	2 (<0.0)
Natural Gas (including CCS)	267 (4.3)	466 (3.3)
Hydro	1031 (16.8)	2187 (15.4)
Nuclear	300 (4.9)	649 (4.6)
Solar	61 (1)	4310 (30.3)
Wind	252 (4.1)	5350 (37.7)
Biomass	6 (0.1)	202 (1.4)
Total	6142	14202

its energy-mix from coal and oil towards renewables, natural gas and nuclear energy generation with changes in the industrialization processes (Bhattacharya et al., 2015). In the ‘Thirteenth Five-Year Plan’ (13th FYP), running from 2016 to 2020, the Chinese Government has set various targets, including the reaffirmed promotion of five million EVs, and has emphasised the importance of the electricity sector to meet increasing electricity demands with low-carbon pathways (Chen et al., 2018). Furthermore, the FYP states that ‘Green is both a necessary condition for ensuring sustainable development and an important way in which people can work to pursue a better life’. The 13th FYP has also quantified guidance on electricity consumption control, stating that China should limit its energy use to five billion metric tons of standard coal equivalent. The target for CO<sub>2</sub> emissions per GDP unit is a reduction of 18% by 2020 compared to 2015. Therefore, to ensure a stable energy supply, fossil fuels will need to be generated during this transition and decreased as renewables are utilised and meet demand.

As China transitions towards a low carbon economy, the introduction of carbon capture and storage (CCS) could be implemented to reduce emissions. CCS is the process where CO<sub>2</sub> is captured and compressed from a large stationary source, i.e. a coal power station, before it is injected into a suitable geological formation for long-term isolation from the atmosphere (Liu and Gallagher, 2010). Due to the high costs of CCS, and limited government subsidies for installation, it has not been implemented on a wide-scale in China (Fan et al., 2019). However, several studies have highlighted that implementing CCS technology alongside EVs promotion will play an important role in protecting the energy transformation sectors, reducing the loss of GDP and reducing emission and oil dependence (Li et al., 2017).

## 2.2. China's ‘leapfrogging’ approach

For this transition towards a low carbon and EV future, China has taken a ‘leapfrogging’ approach, which can be defined in two ways. Firstly, through skipping stages in development and generations of technologies to avoid pollution-intensive stages in development which results in the technology bypassing negative environmental impacts (Goldemberg, 1998; Munasinghe, 1999; Schroeder and Chapman, 2014). Secondly, building on from the first definition, ‘leapfrogging’ also involves jumping further ahead to become a leading technological innovator and utiliser (Gallagher, 2006). By taking this approach for both energy generation and transport, China will be able to become a technological innovator, whilst reducing their use of environmentally damaging technologies.

Whilst ‘leapfrogging’ has relevance to all sorts of areas, it has a resonance in the field of sustainable development, where the need to use cleaner, more energy efficient and less environmentally damaging technologies has never been more urgent (Goldemberg, 1998). By ‘leapfrogging’ technology, China can integrate more developed and low carbon energy systems by skipping over the tried and tested energy systems in developed countries and improving efficiency (Liu et al., 2018). For example, over time the capacity of new solar panels has improved, therefore by installing newer solar panels with the higher capacity level, as opposed to when these solar panels were originally designed, China has the ability to leapfrog over the older technology. This process may allow a reduced level of installation as capacity levels are higher than previously, requiring less area for solar panels. With this continual technological improvement, costs will also begin to decrease. Similarly, the technological improvements of EV battery capacity has allowed individuals to travel further with the same level of charge. This approach has slowly increased the cost-competitiveness of worldwide renewable electricity technologies and of newer EVs. This has led to developing countries, including China, becoming emerging manufacturers and installers of new energy technologies (Bhattacharya et al., 2016). This may also help explain China's predicted rapid expansion of renewable energy technology by 2050 as seen in Table 1.

Following China's initiative of the ‘Ten Cities, Thousand Vehicles’ programme in 2009, the EV market took off due to large-scale projects in various cities (Zhang et al., 2018a). This initiative allowed new consumers to ‘leapfrog’ over petrol and diesel cars and allow first time buyers to purchase

EVs. By 2016, China's EV market was the largest globally with approximately 550,000 registered passenger EVs (Qiao et al., 2017). This accounted for approximately one third of total global EVs (Zhang et al., 2018a). However, with China's current dependence on fossil fuels as an energy source for electricity generation, the environmental benefits will be diminished, unless changes are made.

## 2.3. The UK's emissions and electricity generation

In 2018, transport and energy were the largest emitting sectors producing ~33% and ~27% of total UK GHG emissions respectively (BEIS, 2019b). The Committee on Climate Change (CCC), a UK governmental advisory, body has called for a set of ‘clear, stable and well-designed policies’ to be introduced as they believe current policy is not enough to meet net zero targets (CCC, 2019). To enable the UK to achieve this transition to net zero, the CCC has proposed several five-yearly carbon budgets which currently run to 2032 to ensure the UK Government remains on target to reduce GHG emissions. The UK is currently on their 3rd carbon budget (2018–2022) which aims for a 37% reduction in GHG emissions (the equivalent of 2544 MtCO<sub>2</sub>e) by 2022 compared to 1990 levels. The UK is currently on track to surpass this target, with emissions falling to 42% below 1990 levels in 2016. However, the UK Government believes there will be short-falls within the 4th and 5th carbon budget. With the implementation of policies and proposals in the 2018 Clean Growth Strategy, their impacts will be considered in future policy amendments to reach the net zero target (BEIS, 2018). As part of their emission reduction targets, under the EU European Energy Directive (2018/2001/EU), the UK is committed to generate at least 32% of energy from renewable electricity by 2030, with a sub-target of a minimum of 14% of renewable electricity to be generated for the transport sector.

As seen in Table 2, the scenario (two degree National Grid Scenario) which will allow the UK to meet next zero emission reduction targets based on the projected electricity generation mix in 2017 and 2050 demonstrates a transition away from fossil fuels towards renewables. Furthermore, the UK has a greater diversity of electricity generation types than China, which can lead to an increase in energy security.

As highlighted above, the UK is planning a rapid transition away from coal towards renewable energy technologies. During this transition, gas generation infrastructure for electricity generation is expected to provide dispatchable power when renewable energy technologies cannot meet demand. However, to help balance this, the UK still has interconnectors between France and the Netherlands to encourage peak sharing between different time zones and to reduce power on the UK's National Grid network. To see further benefits, storage technology with an increase in renewable energy generation should be developed. However, this process is not considered zero carbon, and installation of CCS should also be considered in the UK for these circumstances.

**Table 2**

The electricity generation mix in the UK in 2017 and the projected mix in 2050 as a percentage and ratio of total (Source: National Grid, 2018).

	UK (2017) (TWh) (%)	UK (2050) (TWh) (%)
Coal	19.7 (6.5)	0 (0)
Oil	0 (0)	0 (0)
Natural Gas (including CCS)	129.7 (42.8)	31.4 (7.0)
Hydro	4.5 (1.5)	7.1 (1.6)
Nuclear	64.6 (21.3)	116.3 (25.9)
Solar	12.2 (4.0)	42.8 (9.5)
Wind	45.1 (14.9)	196.6 (43.8)
Biomass	16.7 (5.5)	23.2 (5.2)
Geothermal	0 (0)	0 (0)
Marine	0.1 (<0.0)	11.1 (2.5)
Other Renewables	5.1 (1.7)	18.4 (4.1)
Waste	5.4 (1.8)	1.7 (0.4)
Total	303.1	448.6

#### 2.4. The UK's 'phasing' out approach

The Committee on Climate Change (CCC), have stated that transport emissions need to fall by 44% by 2030 for the UK to keep on track to meet its goals under the Paris Agreement. To achieve this, the UK is working towards a 'phasing out' approach which was updated in 2020. This approach involves bringing the ban and sale of all new petrol and diesel cars (and vans) forward from 2040 to 2035, including the sale of hybrid vehicles. The previous 2040 target was under much criticism as studies have highlighted that the UK would struggle to meet their emission reduction targets from road transport. Furthermore, Brand et al. (2020) has suggested that the 2040 target could not be achieved by the continual changes that are currently happening through technological advancements. Whereas a more ambitious target, including the 2035 ban with hybrid vehicles, would require 'disruptive' changes within the existing socio-technical system to decrease GHG emissions. However, these 'phasing out' targets remain ~15 years away and many generations of petrol and diesel vehicles are expected to enter the market beforehand (Brand et al., 2012).

Even with this target being brought forward, cars have a mean life expectancy of 13.9 years before scrapping, therefore any vehicle purchased in 2035 could remain on the roads until 2049 (SMMT, 2019). This will result in the UK's net zero emission target under the Paris Agreement, becoming difficult to achieve. Therefore, to encourage a smooth transition towards EVs, the UK Government has already introduced several grant incentives to reduce purchase and operating costs and facilitate charging installation within homes. Furthermore, with the introduction of several push and pull travel demand management (TDM) initiatives including high road tax for petrol and diesel cars, introduction of ultra-low emission zones in urban areas and higher costs to run petrol and diesel cars, it is anticipated there will be a smooth transition to EVs.

### 3. Methodology and data

To predict the GHG emissions produced by electricity generation for EVs in China and the UK, data were collected from a range of national, regional and local authority databases, including the UK Government and the China National Renewable Energy Centre (Brand et al., 2019; Energy Research Institute, 2015; National Grid, 2018; World Nuclear Association, 2011).

For the purposes of this manuscript, we have focused on analysing the operating emissions of CFVs and EVs. This is primarily due to the lack of long term measurements, monitoring and available data within both countries. A life cycle analysis (LCA) would be too data restricted to give a representative overview for both countries which could result in a number of simplified assumptions, particularly in comparative studies (Klocke et al., 2014). As the highest levels of emissions produced are directly related to the energy generation for EVs, we can assume that the infrastructure and embedded carbon costs will be approximately the same between EVs and CFVs, therefore we have chosen to focus on the operating emissions within our analysis. Although this is a simplified methodology, it focuses on the largest emissions component for the vehicles. The initial infrastructure-related emissions produced for EVs will be high but there is an anticipated reduction in emissions as technology advances over time with the net overall benefits being substantial.

An LCA is a tool used to assess the potential direct and indirect environmental impacts and resources used through a products service (Chester and Horvath, 2009; Hawkins et al., 2013; Helms et al., 2010; Zhang et al., 2019). LCA models are often used to inform stakeholders on a production-consumption chain to allow more informed decision making (Udo de Haes and Heijungs, 2007). Focusing on the operating emissions is beneficial for reducing total GHG emissions, while using an LCA allows policymakers to consider projected cumulative emissions for the future from a whole systems perspective.

However, the manufacture, maintenance and development phases are often not able to be fully parameterised for input into an LCA and may not be included within the model. Although these emissions are

not insignificant, projecting the operating emissions of the vehicle remains in line with current EU policy and China's Fuel Consumption Evaluation Methods and Targets for Passenger Cars policy. It is only recently that Governments and decision making bodies have begun to consider LCAs for critical inputs related to transport fuels (Chester and Horvath, 2009). A fully parameterised LCA would require input data from vehicle manufacturers which is not currently a legal requirement and therefore when making international comparisons this data is unattainable (Logan et al., 2020a, 2020b). Although non-operating factors may not influence the GHG emissions in terms of cost of construction or reusability of materials within the end-of-life phase, as technology evolves, these factors should be considered for a full LCA. Although studies have discussed the environmental impacts of EVs with CFVs, lithium battery packs used in EVs and the influence of electricity generation, this study has developed a simple model to assess and compare the CO<sub>2</sub> operating emissions produced across different countries (Faria et al., 2013, 2012; Hawkins et al., 2013; Majeau-Bettez et al., 2011; Rangaraju et al., 2015; Zackrisson et al., 2010; Zhang et al., 2019).

To estimate the level of CO<sub>2</sub> emissions during the operating phase between 2017 and 2050, two degree scenario data was used for the carbon intensity of the electricity generation mix which would allow both countries to meet their national objectives. In addition, the projected total number of vehicles and the annual distance travelled were projected for both countries and three different vehicle integration scenarios were analysed. These scenarios comprised: (1) only CFVs; (2) only EVs; and (3) 100% EVs and new CFVs banned (see Table 3).

Scenario 1 projected the level of CO<sub>2</sub> emissions if all vehicles were CFVs between 2017 and 2050. Scenario 2 projected the CO<sub>2</sub> emissions if all vehicles were EVs within the time frame. Although it may be considered unrealistic to assume that all vehicles will either be CFVs or EVs by 2050, this analysis can provide a worst case (i.e. 100% CFVs) and a best case (i.e. 100% EVs) scenario in terms of the emissions produced. Within these scenarios, it was assumed that all existing vehicles and new vehicle sales within the time frame fell in line with that given scenario. These scenarios can act as a useful policy tool to give insight into the likely long term benefits in the transition period from CFVs to low emission transport. The worst and best case scenarios depict the upper and lower limits of emissions we would expect with this transport type up to 2050.

To understand the impact of key policy levers in China and the UK, scenario 3 was split into two parts: (3A) with the integration of 50% EVs from 2030 onwards and (3B) with 50% EV integration from 2040 onwards. Although it is unlikely there will be a shift to 50% EVs in one year. i.e. in 2030 or 2040, the rate of integration has varied through both countries different policies for EV integration. Therefore to keep the data comparable, 50% integration was chosen for 2030 and 2040. 2030 was the year China expects their emission levels to peak so a comparison of the ten-years after this occurs may allow further policy to be implemented to understand what can be done to meet emission targets. For the UK, petrol and diesel vehicles are expected to be banned by 2035, therefore predicting the emission levels before and after this date can enable a greater understanding if more needs to be done to achieve targets. Although this is a step change approach, data constraints on likely real world integration rate prohibited us from doing a phased integration approach. It is likely however that these scenarios depict a more realistic picture of the likely emissions outputs if current government policies are fully implemented.

**Table 3**  
Overview of electric vehicle and conventionally fuelled vehicle scenarios.

	Percentage of CFVs in 2017 (%)	Percentage of EVs by 2050 (%)
(1) 100% CFVs	100	0
(2) 100% EVs	0	100
(3A) 50% EVs from 2035 onwards	50	50
(3B) 50% EVs from 2025 onwards	50	50

### 3.1. China - number of vehicles and distance travelled

For China, the official statistics are poor due to the lack of data and the relatively short history of large-scale Chinese motor-vehicle development, especially for private vehicle ownership (Huo et al., 2012), therefore, we refer to other studies. Data from Peng et al. (2018a) were used for the total number of vehicles and total distance travelled. Over the time frame, the total number of vehicles is expected to increase by 268% from 137,570,000 vehicles in 2015 to 507,090,000 vehicles by 2050. This increase in the number of vehicles is due to differences in the development rate of different provinces. For example, eastern provinces generally have lower growth than western and central provinces because they are more sensitive to economic driving forces (Peng et al., 2018a). Relative changes in population and affluence (including vehicle size) were also taken into consideration.

Between 2017 and 2050, the total average annual distance travelled by a private vehicle is forecast to decrease from 15,000 km to 9500 km. This decrease is due to traffic control measures being implemented to reduce congestion, and increased patronage following improvements to public transport (Peng et al., 2018b).

### 3.2. UK - number of vehicles and distance travelled

For the UK, projected number of vehicles and total distance travelled was derived from the Transport Energy and Air Pollution Model (TEAM-UK) (Brand et al., 2012, 2019, 2020). Using the TEAM-UK model, cars were split into three categories: small, medium and large. For the purposes of this study the total number of cars is assumed to increase by 25% from 31,083,476 to 39,001,012 between 2017 and 2050. This increase is partly due to the increase in large vehicles, particularly sports utility vehicles (SUVs) by 27% within the time frame. In the UK, vehicle stock is projected to increase between 2017 and 2050, but at a much lower rate than that of China (SMMT, 2018). This is due to consumer concerns over the emissions produced and current uncertainty from Brexit resulting in less vehicles being bought, before increasing at a higher rate between 2020 and 2050. This is a model assumption that takes into consideration new UK legislation and vehicle life expectancy resulting in a larger number of individuals purchasing new vehicles each decade (TEAM-UK model assumption).

In addition, using the TEAM-UK model, the average annual distance travelled per vehicle decreased by 9.3% over the time frame from 13,170 kilometres in 2017 to 11,948 kilometres in 2050. This decrease is a result of distance projections based upon the need to fulfil demand, which in turn is estimated partly based upon the projected decrease in population size, resulting in a decrease in the need for car usage.

### 3.3. Scenario one – 100% conventionally fuelled vehicles

To estimate the total level of CO<sub>2</sub> emissions from CFVs, Eq. 1 was used.

$$Emissions_{CFVs} = (D * C * G) \quad (1)$$

where D is the average distance travelled per vehicle (km), C is the estimated number of vehicles in 2050, and G is the grams of carbon dioxide per kilometre travelled (gCO<sub>2</sub> km<sup>-1</sup>). Data units are converted to present in MtCO<sub>2</sub>.

To ensure consistency between both China and the UK, the same values for the gCO<sub>2</sub> km<sup>-1</sup> travelled were used. This is because China's emission standards are almost identical to Europe's in terms of limit values, test cycles and other parameters, with the national target translating to 120 gCO<sub>2</sub> km<sup>-1</sup> by 2020 under China's Fuel Consumption Evaluation Methods and Targets for Passenger Cars (GB 27999-2014) (Ben Dror et al., 2019). In the EU, the average car in 2018 produced around 120 gCO<sub>2</sub> km<sup>-1</sup>, below their target of 130 gCO<sub>2</sub> km<sup>-1</sup>. Therefore, to account for vehicle improvements, from 2017 the 120 gCO<sub>2</sub> km<sup>-1</sup> value was used and decreased by 1 gCO<sub>2</sub> km<sup>-1</sup> for each year analysed, resulting in 87 gCO<sub>2</sub> km<sup>-1</sup> by 2050. The value only decreased by 1 gCO<sub>2</sub> km<sup>-1</sup> as from the end of

2020, all new cars within the EU have a limit of 95 gCO<sub>2</sub> km<sup>-1</sup>. Therefore, as the average scrappage age of a vehicle is ~14 years, this would account for vehicle turn over within the time frame. Although this is an ambitious target for both the UK and China as both countries transition away from CFVs, unless this coincides with substantial behavioural changes around new vehicle purchases, this value may be higher.

### 3.4. Scenario two - 100% electric vehicles

To assess scenario two, 100% EVs in 2050, Eq. (2) was used.

$$Emissions_{EVs} = (D * C * (CI * K) * F.) \quad (2)$$

where CI is the carbon intensity of electricity generation (gCO<sub>2</sub> kWh<sup>-1</sup>), K is the energy stored within an EV battery per kilometre (kWh km<sup>-1</sup>) and F is a correctional factor for energy production inefficiencies.

For China, the carbon intensity of electricity generation was estimated using the values from Table 1 and proportionally multiplying these values with the global average life cycle of GHG emissions for the different energy types (Appendix A). The carbon intensity for electricity generation in the UK was based on the National Grid's two degree scenario. This scenario reflects the UK adhering to the global ambition to restrict global temperature rise to below the 2 °C above pre-industrial levels, as set out in the Paris Agreement. This scenario provides large-scale solutions with consumers expected to choose alternative heat and transport options to meet the 2050 targets. Under this scenario, emissions are expected to decrease by 80% from 503 MtCO<sub>2e</sub> in 2017 to 165 MtCO<sub>2e</sub> in 2050. These estimates can be seen in Appendix B.

To account for losses due to both electricity transmission F was given the inverse correctional factor of 6.5% for China (Peng et al., 2018b). For the UK, F was given the inverse value of 8% of electricity lost through transmission (The UK Parliament, 2014). Power conversion is also expected to improve, but limited information quantifying this is currently available. This means that both current and 2050 scenarios were run with the correctional factors of 1.06 and 1.08 for China and the UK respectively, therefore energy required by EVs in 2050 may be overestimated.

Furthermore, K was given a value of 0.17 kWh km<sup>-1</sup> as this is the battery performance of an EV. Although technological advances are likely to happen within this time frame, these improvements are unknown, therefore for consistency this value was used for both China and the UK until 2050.

### 3.5. Scenario three - integration of CFVs and EVs

To calculate total emissions in a scenario with 50% of CFV and 50% EVs in 2030 and in 2040, Eq. (3) was used:

$$Total\ Emissions_{50:50} = ((Equ1CFVs) * 0.5) + (Equ2(EVs) * 0.5) \quad (3)$$

## 4. Results and discussion

The results have been split into five sections. The first three sections discuss the outputs of the model under all vehicle mix scenarios (Sections 4.1–4.3). An overview of the results in these sections can be seen in Appendix C. Section 4.4 discusses and compares the cumulative emissions of all three scenarios and Section 4.5 projects the total energy required to fuel EVs in 2017 and 2050 based on both countries expected electricity generation mix.

### 4.1. Scenario one – Conventionally fuelled vehicles

Under scenario one (as seen in Table 4), the level of emissions produced in China increases from 247.6 MtCO<sub>2</sub> in 2017, peaking in 2030 at 547 MtCO<sub>2e</sub>, before decreasing to 419 MtCO<sub>2</sub> by 2050. This increase in the level of emissions is due to the rapid increase in number of vehicles between 2017 and

**Table 4**

Total carbon dioxide emissions and emissions produced per kilometre travelled for China and the UK between 2017 and 2050 under scenario one.

	China		UK	
	Total CO <sub>2</sub> emissions (MtCO <sub>2</sub> )	Kilograms of CO <sub>2</sub> per vehicle per (kgCO <sub>2</sub> per vehicle)	Total CO <sub>2</sub> emissions (MtCO <sub>2</sub> )	Kilograms of CO <sub>2</sub> per vehicle per (kgCO <sub>2</sub> per vehicle)
2017	247.6	1800.0	49.1	1580.4
2020	415.7	1673.1	48.7	1525.4
2030	547.4	1230.5	46.7	1357.7
2040	489.8	970.0	43.8	1191.1
2050	419.1	826.5	40.5	1039.5

2030 of 233% compared to an increase of 13% between 2030 and 2050. This, coupled with a decrease in distance travelled within the time frame, likely highlights why the increase is not greater. However, the kgCO<sub>2</sub> per vehicle decreases by 54% from 1800 kgCO<sub>2</sub> per vehicle to 826.5 kgCO<sub>2</sub> per vehicle within the time frame highlighting that although total emissions from CFVs will increase, emissions per vehicle are decreasing. Thus, further highlighting that an increase in vehicle numbers is a major factor in the total level of road transport emissions in China.

Under this scenario, for the UK, CO<sub>2</sub> emissions are expected to steadily decrease between 2017 and 2050 from 49.1 MtCO<sub>2</sub> to 40.5 MtCO<sub>2</sub>. Furthermore, per vehicle emissions decreased by 34% from 1580.4 kgCO<sub>2</sub> per vehicle to 1039.5 kgCO<sub>2</sub> per vehicle. Therefore, emissions per vehicle remained higher for CFVs in the UK than for China.

These results highlight that, even with technological improvements, i.e. to meet the target of emissions produced per kilometre travelled decreasing from 120 gCO<sub>2</sub> km<sup>-1</sup> to 87 gCO<sub>2</sub> km<sup>-1</sup>, for both China and the UK emissions are unlikely to decrease to meet Paris Agreement objectives.

#### 4.2. Scenario two – Electric vehicles

Under scenario 2, China is expected to see a reduction in CO<sub>2</sub> emissions by 55% from 239 MtCO<sub>2</sub> in 2017 to 107 MtCO<sub>2</sub> in 2050 as seen in Table 5. Similar to scenario one, emission levels are expected to peak in 2030 at MtCO<sub>2</sub>. Under this scenario, emissions per vehicle in China are expected to decrease by 88% from 1737.6 kgCO<sub>2</sub> per vehicle in 2017 to 211.5 kgCO<sub>2</sub> per vehicle by 2050. This significant decrease in total emissions and emissions per vehicle is due to the decrease in the level of fossil fuels expected to be in the energy generation mix and the shift to renewables.

For the UK, if all vehicles were electric, CO<sub>2</sub> emissions are expected to decrease by 92% from 20 MtCO<sub>2</sub> in 2017 to 1.7 MtCO<sub>2</sub> in 2050. Similarly, emissions per vehicle are expected to decrease by 93% from 643.2 kgCO<sub>2</sub> per vehicle in 2017 to 43.4 kgCO<sub>2</sub> per vehicle by 2050. Similar to China, this decrease in emission levels is due to the proportional decrease of fossil fuels within the electricity generation mix between 2017 and 2050.

**Table 5**

Total carbon dioxide emissions and emissions produced per kilometre travelled for China and the UK between 2017 and 2050 under scenario two.

	China		UK	
	Total CO <sub>2</sub> emissions (MtCO <sub>2</sub> )	Kilograms of CO <sub>2</sub> per vehicle per (kgCO <sub>2</sub> per vehicle)	Total CO <sub>2</sub> emissions (MtCO <sub>2</sub> )	Kilograms of CO <sub>2</sub> per vehicle per (kgCO <sub>2</sub> per vehicle)
2017	239	1737.6	20.0	643.2
2020	380	1529.7	11.1	347.3
2030	369	830.5	3.8	110.9
2040	176	349.3	1.6	44.4
2050	107	211.5	1.7	43.4

**Table 6**

Projected carbon dioxide emissions produced (based on the energy generation scenarios for China and the UK) for EVs to be 50% integrated from 2030 (Scenario 3A) and 2040 (Scenario 3B) onward.

	Scenario 3A China (MtCO <sub>2</sub> )	Scenario 3B China (MtCO <sub>2</sub> )	Scenario 3A UK (MtCO <sub>2</sub> )	Scenario 3B UK (MtCO <sub>2</sub> )
2017	239.0	247.6	49.1	49.1
2020	380.0	415.7	48.7	48.7
2030	458.5	547.4	25.3	46.7
2040	333.1	333.1	22.7	22.7
2050	263.2	263.2	21.1	21.1

#### 4.3. Scenario three A and three B

Table 6 demonstrates the integration approach with all vehicles expected to be 50% EV from 2030 onwards under scenario 3A and then under scenario 3B with 50% of vehicles EV from 2040.

Results indicate that for China, emission levels are expected to peak in 2030 under both scenario 3A and scenario 3B, however emission levels are lower under scenario 3B. Alternatively, the UK has seen a decline in emissions under both scenarios, however as expected there is a greater level of decline under scenario 3B.

#### 4.4. Cumulative emissions

Assuming a linear relationship between the ten-year time steps, cumulative emissions under all three scenarios were estimated based on the ten-year time step data available as seen in Table 7.

Schest level of cumulative emissions for both countries, the equivalent of 1.7 times higher in China and 8.9 times higher in the UK than scenario two. Integrating EVs under scenario three A saw an increase of 11% from scenario two in China and 285% in the UK, whereas integrating EVs under scenario three B saw an increase of 37% in China and 530% in the UK in comparison to scenario two. Results therefore highlight the importance of early EV implementation to reduce CO<sub>2</sub> emission in both China and the UK.

#### 4.5. Energy generation for a full EV fleet

Table 8 highlights the projected total energy required to fuel an entire EV fleet in China and the UK between 2017 and in 2050. Within this time frame, China will need to increase transport energy demand by 133%, however taking into consideration the energy demand peak in 2030 at

**Table 7**

Projected cumulative emissions under all three scenarios for China and the UK between 2017 and 2050.

	China's cumulative emissions (MtCO <sub>2</sub> )	UK's cumulative emissions (MtCO <sub>2</sub> )
Scenario one	16018.4	1543.8
Scenario two	9176.9	174.1
Scenario three A	10,179.2	671.6
Scenario three B	12578.4	1097.7

**Table 8**

Projected energy required to fuel a fleet of electric vehicles in China and the UK between 2017 and 2050 in gigawatt hours.

	China (GWh)	UK (GWh)
2017	373500.5	75159.0
2020	643111.3	76470.4
2030	926033.4	80111.5
2040	913882.1	82841.3
2050	871936.4	85552.8

926,033.4 GWh, energy generation will need to increase by 148% from 2017. In the UK, energy demand increases steadily, increasing by 14% from 75,159.0 GWh to 85,552.8 GWh between 2017 and 2050.

## 5. Discussion

Results have highlighted that if China and the UK want to meet their Paris Agreement targets, immediate action is required for a shift towards EVs based on decarbonised electricity generation. Under the scenario which would allow both countries to meet their emission reduction targets, it is expected that emission levels will peak in China by 2030, with the UK having a more gradual decline in the level of emissions produced. Furthermore, when comparing the  $\text{kgCO}_2 \text{ km}^{-1}$  per vehicle, values remain higher for China than in the UK. As demonstrated under Scenario 1, technological improvements in CFVs are not enough to significantly reduce the GHG emissions or the  $\text{gCO}_2 \text{ km}^{-1}$  per vehicle within the time frame. By encouraging a modal shift earlier (as highlighted in scenarios 3A and 3B), cumulative emissions were much lower. However, EVs are not a panacea to meet the targets for either country and the need for decarbonisation of electricity generation will be required to reduce emissions from transport.

In addition, studies have highlighted that for all types of transport, by reducing the operating emissions of a vehicle, the overall LCA emissions will reduce. This is primarily due to focus being placed on technological advancement through environmental optimization of vehicle design and manufacturing processes making improvements over time to stay in line with policy (Chanaron, 2007; Danilecki et al., 2017). This has been further highlighted under the policies already implemented in both China and the UK. Furthermore, LCAs are often not applicable due to data deficiencies therefore operation based studies through simple models have a much greater utility within international comparisons. Therefore, using the approach taken within this research, emission comparison per car per kilometre driven allowed direct comparison. Through this approach to analysis countries then have the ability to learn from one another as low carbon energy generation and transport is integrated into their respective transport networks. Furthermore, before settling on the methodology used within this analysis, LCA models were considered for analysis. This included the Long-range Energy Alternatives Planning system (LEAP) which is a software tool for energy policy analysis and climate change mitigation assessment (Heaps, 2008). Over the past decade this model has been used for multiple countries including Pakistan, China, Colombia, Korea and Taiwan through a national approach applied to cities and regions (Cai et al., 2013; Huang et al., 2011; Paez et al., 2017; Perwez et al., 2015; Shabbir and Ahmad, 2010; Shin et al., 2005). However, this method required substantial data including information regarding industrial processes, solid waste, land use change and forestry which was not readily available. Therefore, increased data will be required to run the model effectively. Taking a simpler operating emissions approach allows comparisons between developed and less developed countries as it doesn't quantitatively underrepresent the true costs and subsequent total emission targets being met.

For both China and the UK, the average number of vehicles is expected to increase, with the average distance travelled annually decreasing. Both countries are in the fortunate position that most vehicle manufacturers in country have begun to produce EVs to meet the demand, with China being a global leader in EV manufacture. This may result in a decrease in the costs associated with EVs, undercutting the cost of CFVs and encouraging EV adoption. Therefore encouraging a modal shift towards low carbon electric and hydrogen public transport will reduce the incidence of single occupancy travel and reduce the level of emissions produced per person (Logan et al., 2020a, 2020b).

For widespread EV implementation in both countries to be fully realized, several obstacles will need to be overcome. EVs need to remain appealing for consumers in terms of cost. Using the same emission efficiency value of  $120 \text{ gCO}_2 \text{ km}^{-1}$  that we used in the analysis, it is \$7.60 per 100 kilometres for a CFV. Similarly, using the same efficiency value of  $17 \text{ kWh } 100 \text{ km}^{-1}$ , it costs \$3.09 per 100 kilometres to fuel an

EV in the UK. In China, the maximum charging fee per kWh varies, therefore costs range from \$5.95 per 100 kilometres in Jiangxi to \$1.14 per 100 kilometres in Taiyuan (Hove and Sandalow, 2019). This example calculation highlights that in both countries it will likely be cheaper to use EVs than CFVs as the cost of electricity is lower than the cost of fuel for CFVs, however upfront costs of new vehicles often hinder individuals purchasing new EVs (Hove and Sandalow, 2019). These results indicate that in some provinces it is cheaper to fuel an EV in China in comparison to the UK. Using this method for comparing the usage running cost of a vehicle per 100 kilometres can enable policymakers to demonstrate the difference in the cost of a vehicle to actively encourage new vehicle owners to 'leapfrog' CFVs towards EVs, though as just demonstrated this still needs work.

As mentioned, the cost of EVs is expected to decrease, however after the vehicle is purchased electricity generation needs to be taken into consideration. Therefore, vehicle battery charging should occur, where possible, during off-peak electricity demand times, and electricity stored to reduce costs. Most individuals will choose to charge their vehicles after they have returned home from work, which is traditionally peak electricity demand time, thus causing strain on the grid network. By introducing an EV smart meter charging controller to provide multiple ancillary services, for example, congestion management, local voltage support or as an autonomous controller implemented directly in the EV supply equipment for local voltage regulation, the impact on the grid can be reduced individually (Knezovic et al., 2017). Furthermore, the placement of EV charging is important to consider as network investment costs are passed to the final consumer as an increase in energy marginal costs. Therefore an expensive charging scheme with a higher network investment and more expensive electricity generation will translate to higher energy bills to the final consumer (Calvillo and Turner, 2020). This has the potential to cause a cascading effect which will result in an increase in prices, with an impact particularly for those within lower incomes who may not necessarily benefit from having an EV. Therefore when designing and introducing new policies, costs and benefits to the whole economy needs to be taken into consideration (Calvillo and Turner, 2020). To reduce these costs as far as possible, electricity should be generated during off-peak times and stored.

Although researchers have studied the utilisation of EV batteries as energy storage in the power system to balance demand and supply, whilst maintaining the stability of the grid, there is not yet the widespread technology to store electricity in either China or the UK at such a high level (Aziz et al., 2015; Hodge et al., 2010; Huda et al., 2020). Smart meters will allow more coordinated timing of widespread charging of EVs, which has the potential to reduce the demand on the grid to ensure charging doesn't negatively impact on peak demand times. It was out with the scope of this study however widescale EVs have the potential to be used as fluctuating energy stores to help cope with broader energy network demands as long as the network infrastructure is developed with this consideration in mind. Furthermore, to actively encourage modal shift to public transport, the introduction of TDM initiatives including free parking for EV users, low cost charging facilitates, reduced tax costs compared to CFV users or allowing individuals to drive in bus lanes may encourage uptake. Thirdly, convenience remains a key factor limiting uptake. Ensuring sufficient charging facilities for EVs are available through accessible real-time information about public charging points, and through tax incentives for charging facilities at homes may encourage uptake.

Even if EV uptake is high, both countries face issues when it comes to integrating renewable energy generation into their mix and ensuring energy security. Although China has already become a leader within the global renewable energy industry, due to socio-economic, energy policies and the economic viability of large scale renewable energy generation, they have fallen behind in terms of implementation (Wang et al., 2018). Therefore, introducing policies that allow large scale implementation at an affordable cost may likely take time, however, through their 'leapfrogging' approach, technological advancements may allow China to require less new generating infrastructure than before. On the other hand, the UK has already developed a diverse energy generation mix, but there remains a lack of consistency between policies. For example, the UK has three

devolved national administrations which each have different policy targets. By ensuring a more centralized approach with more aggressive targets both countries are more likely to meet the Paris Agreement (and further on) for the 2 °C limit of global warming. Furthermore, increasing the production of low carbon energy alone has been considered less effective than reducing fossil fuel consumption, as this does not take into consideration the collective behaviours of energy users in the political, social, cultural and economic contexts. Therefore, to encourage this shift towards renewables, market instruments, including fuel tax and incentives, can help to promote low carbon energy whilst reducing consumption in fossil fuel use. For example, China's electricity prices are set by the Central Government whereas coal price is determined by the market (Zhang et al., 2018b).

Alternatively, the UK Government has integrated a policy combining carbon taxes, non-fossil fuels and energy efficiency (Greening et al., 2000; Herring, 2006). This involves the UK charging a carbon cost through renewable obligation certificates, whilst incentivising low carbon energy generation through feed-in tariffs (FITs) and Contract for Difference (CfDs) schemes. Any money generated from this can then subsidise additional renewable energy construction, replacing fossil fuels, and allowing renewable energy to become more affordable. Furthermore, the UK will likely see economic benefit from this transition away from CFVs within the wider economy. As although it is commonly argued that fossil fuels are an important source of tax revenue, through linked economic modelling work, several studies have highlighted that the uptake of EVs could trigger other benefits offsetting any losses incurred (Alabi et al., 2020; Calvillo and Turner, 2020; Turner et al., 2018). This is primarily because CFVs are part of an import-intensive supply chain as opposed to the UK electricity generation industry which has a strong domestic supply chain so this growth is likely to have a more positive impact within the wider UK economy (Calvillo and Turner, 2020; Turner et al., 2018). Therefore although there may be higher start-up costs in the UK for widespread EV integration in terms of additional energy and infrastructure, the overall benefits of EVs outweighs this long term.

Although both countries are moving towards renewables, there remains a large potential for energy efficiency improvements within the energy generation process to reduce emissions. This is due to almost ~10% of electricity generation being lost during transmission, distribution and under-utilisation (Hu and Cheng, 2017). However, the Jevons Paradox states that by increasing the productivity of the commodity, greater consumption of that commodity can occur, and this has long been discussed in economic and political research. Therefore improved energy efficiency within China and the UK's energy generation network may be partially or even fully cancelled out due to greater consumption of energy stimulated by the lower cost of energy services (Herring, 2006; Hu and Cheng, 2017; Madlener and Alcott, 2009; Mizobuchi, 2008; Polimeni and Polimeni, 2006). However, this rebound effect is limited, offsetting by between 20 and 60% of the expected savings (Gillingham et al., 2013; Greening et al., 2000; Polimeni and Polimeni, 2006). Therefore, if both China and the UK want to see improvements within their network, whilst encouraging this shift towards renewables, both countries need to ensure that energy generation is being used sensibly, or environmental benefits may be diminished. By introducing policies that combine improvements within efficiency with conservation policies, this will allow maximum benefits from the installation of renewable energy generation.

Overall, our results highlight that reducing China's and the UK's GHG emissions produced from transport cannot simply rely on renewables and energy efficiency. Enhancing existing technologies, during the transition towards decarbonised electricity generation, through the incorporation of CCS or selective catalytic reductions and coal cleaning, a reduction of emissions from China's coal generation processes (as well as on a global scale) could potentially be achieved through improved energy efficiency (Jiang and Green, 2018). This would allow a smoother transition towards low carbon, whilst renewable energy generation is still being constructed while ensuring energy demand is met. Providing subsidies or tax benefits and training opportunities for individuals to develop new skills within this sector, will encourage this switch. Through

these enhancements, there is the possibility to reduce the electricity transmission and distribution line loss. Also, energy conservation targets should be set for energy-intensive sectors to reduce energy waste. China has already 'leapfrogged' the UK, as all new power stations are combined heat and power whilst being driven by heat demand, even if they are coal. This may provide a better incentive to move away from thermal power stations as there will be a need to substitute for provision of heat and move to other sustainable sources. However, in some provinces of China, 'renewable generation blindness' has occurred, where installation of solar and wind were fitted in locations which did not have the best conditions to maximise efficiency. Through improved communication within government, experts and locals, the best possible locations for renewable energy can result in a better output of electricity generation. In addition, China needs to develop EVs rapidly in regions with cleaner power and promote other energy efficiency and other alternative low carbon energy vehicles i.e. hydrogen vehicles in regions which are not as developed yet.

## 6. Conclusions

Results from this study indicate that technological improvements of CFVs will not be enough for China or the UK to meet their national targets as part of their Paris Agreement objectives. Therefore, introduction of EVs will be essential to reduce GHG emissions from road transport in both countries. Results indicate that early integration of EVs will significantly reduce both countries' cumulative emissions. In the case of China this is achieved by encouraging a 'leapfrogging' approach with new consumers, while the UK has adopted a 'phasing out' approach for older CFVs.

Furthermore, as both countries adapt to EVs, additional energy will need to be generated to meet demand. Results indicate China's CO<sub>2</sub> emissions are expected to peak in 2030, before decreasing, with UK emissions steadily decreasing within the time frame. Although both countries will need to continue the decarbonisation of electricity generation to reduce GHG emissions, China will also need to consider diversifying their electricity generation mix to improve energy security. Both countries will need to ensure that energy generation is being used sensibly, or environmental benefits may be diminished. In addition, both countries can benefit from the installation of CCS as they transition towards low carbon energy generation by ensuring energy demand is being met, whilst mitigating GHG emissions produced from fossil fuels.

Overall, earlier EV adoption with decarbonised electricity generation will be necessary. To achieve this, policymakers should focus on introducing new policy combining carbon taxes, non-fossil fuels and energy efficiency, with any financial profits reinvested to subsidise for renewable energy construction, replacing fossil fuels, so allowing renewable energy to become more affordable.

## CRedit authorship contribution statement

**Kathryn G Logan:** Writing - original draft, Writing - review & editing, Conceptualising, Methodology, Data curation, Formal analysis.

**Astley Hastings:** Conceptualization, Resources, Writing - review & editing, Supervision.

**John D. Nelson:** Conceptualization, Resources, Writing - review & editing, Supervision.

**Xi Lu:** Conceptualization, Data curation, Resources, Writing - review & editing.

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## Appendices. Supplementary data

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