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Japan and the UK: Emission predictions of electric and hydrogen trains to 2050

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A B S T R A C T

Electric trains (ETs) and hydrogen trains (HTs) offer an opportunity for both Japan and the UK to meet their national targets as part of the Paris Agreement. Although ETs and HTs are considered zero emission at the point of use, their true environmental impact is dependent upon non-tailpipe emissions from fuel/energy production and vehicle manufacture, maintenance and disposal. To assess and compare the carbon dioxide emissions produced from ETs and HTs in Japan and the UK from 2020 and 2050, the operating emissions of these trains were projected. Results compared ET and HT emissions with diesel fuelled trains (DFTs) to better assess which fuel type was the most environmentally friendly. Emissions per train, cumulative emissions and total energy required for ETs and HTs were compared.

Results indicated that even with technological improvements, DD DFTs produced the highest level of emissions in both countries, followed by HTs. Although ETs produced the lowest level of emissions, it is likely that a mix of both ETs and HTs will be required to meet passenger demand and for travel within rural areas. As Japan has already transitioned towards ETs, future policy focus should be placed on decarbonisation of their energy sector and a shift away from fossil fuels in favour of renewable energy, otherwise environmental benefits of ETs will be diminished. As the UK is decarbonising its electricity network, focus needs to be placed on electrifying the majority of the rail network and running the rest on hydrogen to decarbonise rail transport.

Introduction

The 2015 Paris Agreement aims to limit global warming to well below 2 ˚C above pre-industrial temperatures and to pursue efforts to limit temperatures to 1.5 ˚C above pre-industrial levels (Rogelj et al., 2016). As part of this agreement, both Japan and the UK have set their own nationally determined contributions (NDCs), with Japan aiming to reduce their greenhouse gas (GHG) emissions by 80% compared to the 1990 baseline levels by 2050 (Ashina et al., 2012). The UK has set a more stringent target aiming for net zero GHG emissions by 2050 (equivalent of 95% compared to 1990 base line) (O'Beirne et al., 2020). For these international and national targets to be met, both countries need to focus on reducing transport emissions, as these contributed to 18% of Japan's national GHG emissions total and 28% of the UK's in 2017 (CCC, 2018; Watabe et al., 2019). Personal road transport emits more carbon dioxide (CO_2) on average than other land transport modes, i.e. bus and rail (Shiraki et al., 2020), therefore shifting towards a higher share of public and mass transit will be essential (Chaturvedi and Kim, 2015; Hensher, 2007).

Rail-based passenger transport is an important element in the public transport sector in many countries and cities (Chaturvedi and Kim, 2015). Globally, rail is considered to be one of the more environmentally clean means of transportation per capita, despite producing ~3.6% of global transport emissions and consuming ~2.1% of global transport energy consumption (Ghaviha et al., 2017; Hayashiya, 2017). Rail emits comparatively lower emissions per capita. For example, in the UK, the projected grams of CO_2 produced per kilometre per person by regional diesel fuelled trains (DFTs) was one sixth of private conventionally fuelled vehicles (CFVs) at 100%, 75%, 50% and 25% capacity (assuming 100% capacity equates to 447 train passengers

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and four car passengers) (Logan et al., 2020a). Rail is one of the few transport types to have decreased CO_2 emission trends as global CO_2 emissions have increased (Ghaviha et al., 2017; IEA, 2017).

By encouraging and improving low carbon rail, including electric trains (ETs) and hydrogen trains (HTs), both Japan and the UK are likely to see a reduction in GHG emissions across the rail network. The aim of this paper is to assess the CO_2 emissions produced from diesel fuelled trains (DFTs), ETs and HTs in Japan and the UK between 2017 and 2050. For the purposes of this study, only passenger transport is investigated. The methods used within this paper focus on the tailpipe emissions of passenger rail within both countries. This novel comparison of projected rail emissions will enable a better understanding of the influence of the electricity generation mix in both Japan and the UK. We are not aware of previous studies utilising national generation data sets for an international comparison focusing on Japan and the UK. Furthermore, cumulative rail emissions and transport emissions per person per kilometre travelled will also be investigated to better understand which method of rail travel is the least carbon intensive as both countries work towards the Paris Agreement.

This comparison between Japan and the UK was chosen as both countries have different railway histories and electricity networks which will allow us to gain a better understanding of how the energy sector needs to be adjusted to establish low carbon rail into the transport and energy networks, whilst decreasing GHG emissions. For an overview of current and future electrified rail in Japan see Oura et al., (1998) and for the UK see Smithers (2020). Compared both countries have very different methods to meet their targets. Japan has been considered a global forerunner by integrating high speed rail and encouraging consumer uptake through a fast, low carbon and efficient service for long distance journeys, reducing the need to fly. Alternatively, the UK continues to use DFTs, which will be phased out from 2040, but the UK rail system has a low user uptake over longer journeys. With this comparison, relevant recommendations for policymakers can be made to assess how both countries can reduce their transport emissions in order to meet their emission reduction objectives.

Although both countries face a similar demographic in terms of an ageing population, differences in projected population size changes over the next thirty years need to be considered when designing the transport network. Japan faces a decreasing population size, which may reduce the demand for public transport. Rail travel represents the dominant transport choice with 30% of people travelling by rail within metropolitan areas in Tokyo, approximately the same as cars (Abe and Kato, 2017). Overall, Japanese use of rail accounts for up to 72% passenger distance travelled (Statistica, 2020). Whilst this may change as the percentage of the working population fluctuates, this highlights the need for a decarbonised rail network. On the other hand, the UK's population is currently almost half that of Japan at ~67.3 million in 2020 and is expected to increase to ~76 million in 2050 (Byers et al., 2014; ONS, 2017). Therefore, a reliable transport network is essential. Furthermore, Japan has a land area that covers 364,560 km^2 whereas UK area covers 248,532 km^2, however Japan's rail network is much more developed and relied upon for longer distance travel. Higher usage may be attributed to the introduction of the Aviation Fuel Tax in Japan, something the UK has not yet imposed, though differences may also be due to Japan's significantly more extensive rail infrastructure providing greater convenience (González and Hosoda, 2016). However, there has been limited decreases in air travel (Liu et al., 2019). As the UK's land area is 1.5 times smaller than Japan, integrating a low carbon rail service that is comparatively lower cost and convenient may encourage uptake of more sustainable transport options.

Whilst trains offer a cleaner transport method, the benefits of switching to higher train usage will be partially negated if trains are not powered by hydrogen and/or electricity generated from low carbon (e.g. renewable or nuclear) resources. Both Japan and the UK are focussing on transforming their electricity generation mix with country specific energy transitions. Japan has low electricity generation diversification and is heavily dependent upon limited resources of fossil fuel imports which have increased in prevalence since local nuclear power generation disruptions due to the 2011 Fukushima nuclear accident. The UK has a much more diverse energy mix with ~33% of electricity generated from renewables (including wind, solar and tidal) and an additional 21% from nuclear energy generation (BEIS, 2019a). The UK currently generates ~39.5% of energy generation from natural gas, with unabated coal being phased out from 2025 (BEIS, 2019a; 2018a). Government policies regarding generation mix should focus on low greenhouse gas emission electricity sources to ensure transitioning to alternative transport power is not simply shifting emissions elsewhere.

Both countries in this study began to introduce and invest in electric rail for different reasons and during different time frames. Japan began to introduce electric rail lines in the 1940s and 1950s to carry domestic freight after World War II, replacing steam trains (Yamamoto, 1993). Transitioning to electrified rail allowed Japan to consume less coal and alleviate the coal shortages. Policy introduced at the time supported this through hydroelectric generation to power ETs. ETs A majority of electricity was to be hydroelectrically generated with thermoelectric power as a secondary source (Yamamoto, 1993). Alternatively, the UK utilised steam trains until the 1970s due to coal availability, unlike in Japan. However steam trains were replaced largely by diesel trains throughout the country. London was the exception where almost a third of rail was electrified from the 1890s spreading through to the south coast by the 1930s. With the steady migration to DFTs and the availability of North Sea oil, the urgency in the UK to transition to electric rail has been slow. However to meet the UKs new emission reduction targets as part of the Paris Agreement, this transition will be needed.

The Japanese rail system is a major means of passenger transport and is provided by six passenger Japanese Railway (JR) companies, responsible for providing 20,117 million kilometres in 2016 (Mizutani and Fukuda, 2020). An additional train line called JR-Freight, responsible for the transportation of freight, travelled 35.5 million kilometres across 2016 (Mizutani and Fukuda, 2020). The remaining network is controlled by other private railway companies (16), semi-major companies (5), public authorities (11), small-to-moderate private railway companies (128); there are also some monorails, new transit systems and cable railways (33) (Kurosaki and Economics, 2017). As of March 2003, 55% of Japan's conventional rail line was electrified with 100% of the high speed Shinkansen electric (Kobayashi, 2005). In 1964, Japan introduced the world's first high speed railway (HSR), the Japanese Tokaido Shinkansen, which use multiple electric units offering fast acceleration, deceleration and whilst also reducing track damage due to the lighter weight of electric HSR trains. In 2019, it was announced that the JR-East planned to test trains using hydrogen fuel cells from 2021. Hydrogen fuel cell trains were previously explored in Japan in 2001 by Japan's Railway Technical Research Institute, however plans were stopped due to problems related to fuel cell fuel performance (Haseli et al., 2008). Hydrogen fuel cell trains are not a new concept with developments by Steinberg and Scott (1984) comparing fuel and energy consumption of rail locomotives using hydrogen and other modes of propulsion against conventional diesel-electric locomotives and other trains (Haseli et al., 2008). This study showed alternative powered rail had some advantages but was reliant on the relevant infrastructure being in place.

On the other hand, the UK's rail infrastructure is run by a public company called Network Rail (NR) which is answerable to the UK Government, with trains, smaller stations and routes operated by 16 franchises run by private companies (although two have been taken back under Government control). Abolition of the franchising system was announced in September 2020 (Macola, 2020). In 2018, the UK

Government announced plans to phase out 'diesel-only' trains (which currently account for ~29% of locomotives) on Britain's railways by 2040, however as only 37% of the current rail tracks are electrified, significant investment and changes may need to be made before this phasing out can be successful. A current proposal is for 'bi-mode' trains which allow train traction units to switch between electrified and non-electrified tracks and these are being tested on the Great Western and InterCity Eastern Coast Routes. Alternatively, hydrogen rail traction is currently being tested in the UK, with the first hydrogen fuel cell trains projected to run by 2022. Therefore, reliable emission projections are important for policy makers to better understand the potential emissions before widespread integration of alternatively fuelled trains occurs (Logan et al., 2020a).

Japanese rail networks

The railway network in Japan plays a central role in society by extensively covering most major islands and provides services for mass high speed travel between major cities and for commuter transport in metropolitan areas (Lam and Tai, 2020). In 2017, Japan had the third highest number of passenger kilometres travelled globally that year with almost 440 million passenger kilometres recorded. Although the market share of railways has been decreasing over time, the railway sector still accounts for 29% of the transport market in terms of passenger kilometres (Kurosaki, 2018).

Prior to the Tokyo Olympics in 1964, Japan introduced its first high speed train (also known as Shinkansen) connecting Tokyo to Osaka. This reduced travel time by two and a half hours over the 513 km journey (Bracaglia et al., 2020; Liu et al., 2019). With the public's positive response to the rail service, there was a significant expansion between the 1970s and 1990s, with relatively minor expansions occurring after this. Japan has a relatively mature advanced rail network connecting all major cities (Liu et al., 2019). Furthermore only 1% of trains are still expected to run entirely on diesel fuel in 2040, therefore decarbonisation of electricity supply will be critical to decarbonise rail transport (ERIA, 2019).

Japan's energy targets and electricity generation

Japanese railways consumed ~17.7 TWh of electric energy in 2013, the equivalent of 1.9% of total electric energy supply in Japan, and this has the potential to produce significant levels of emissions when energy generation is primarily from non-renewables (Hayashiya, 2017). This has led to many railway companies within Japan aiming to reduce their energy consumption to meet emission targets. Among solutions to reduce energy consumption is to enhance utilisation of energy and focus on decarbonised electricity for train use.

The reduction of GHG emissions is a major environmental challenge for Japan. In 2016, Japan generated 1.325 $GtCO_2e$ of GHG emissions, contributing to ~3.5% of global GHG emissions (Watabe et al., 2019). After the Fukushima tragedy in 2011, Japan has adjusted their long-term climate and energy policies and retracted their previous goal of 25% emissions reduction from the 1990 levels by 2020 (Sugiyama et al., 2019). In 2015, the Japanese Government submitted its NDC target to reduce the country's GHG emissions by 26% by 2030 from 2013 levels. Japan has also formulated its long-term energy policy and aims to reduce GHG emissions by 80% by 2050 whilst pursing global warming countermeasures and economic growth at the same time (Sugiyama et al., 2019).

Historically, Japan has been considered an energy resource poor country. It is the fifth largest global energy consumer, importing ~94% of primary energy supply in the form of fossil fuels (METI, 2017; Vivoda, 2012). In particular, oil-based fuels which account for ~98% of vehicle fuels, of which ~87% comes from the Middle East (METI, 2017). With such high dependence and demand for energy imports and a previous reliance on nuclear power, energy security has been made a priority by the Japanese Government, particularly as a result of the two oil crises in 1973 and 1979 (Vivoda, 2012). Before Fukushima, nuclear energy accounted for ~25% of Japan's electricity generation, before decreasing to 0% in 2014. Nuclear energy has since increased slowly to 0.9% by 2015 with five nuclear power stations in Japan allowed to operate by September 2017. After Fukushima, gas and other fossil fuel fired power plants fulfilled an estimated electricity supply deficit of ~30% (IEA, 2016) that would have been supplied by nuclear power plants. In this period, energy security has once again become the centre of attention for Japanese policy makers and the general public (Hayashi and Hughes, 2013; Vivoda, 2012). Considering relative costs, availability of thermal electricity technology and availability of fuels, Japan turned to importing fossil fuels, primarily liquefied natural gas (LNG), coal and oil (IEA, 2016). This increased CO_2 emissions from power generation to ~110 Mt, more than 20% between 2010 and 2013 (IEA, 2016).

Future electricity generation in Japan has previously been constrained by three sources of path dependency (Vivoda, 2012). Firstly, public opinion due to the tsunami induced Fukushima disaster. Secondly, energy policy making capacity centred around the Ministry of Economy, Trade and Industry (METI) and the powerful utilities and nuclear industry that are pro-nuclear (Vivoda, 2012). Finally, the relative energy prices and other structural constraints which make nuclear energy and fossil fuels the most economically feasible energy choices (Vivoda, 2012). Therefore, for a successful transition towards a decarbonised electricity network and a shift away from fossil fuels and imports, Japan's energy policy needs to focus on several strategies. Firstly, strengthening energy security by diversifying the energy generation network through the introduction of alternative low carbon resources including solar, wind and tidal energy (Logan et al., 2020c). Secondly, implementing energy conservation and renewable energy policies that consider environmental concerns alongside growth, and finally balancing public opinion against a stable electricity supply, perceived safety and reduced costs.

To achieve this, under the 2002 Basic Act on Energy Policy, Japan has set updated 'Strategic Energy Plans' (SEPs) every three to four years from 2007 taking into account changes in the energy environment inside and outside of Japan (Kucharski and Unesaki, 2017). For example, under the third SEP, Japan set a target of reducing emissions by 6% between 2008 and 2012 compared to 1990 levels under the first commitment period of the Kyoto Protocol (UNFCCC, 2008). However, this plan was heavily dependent on nuclear energy with an anticipated increase in nuclear power share in the electricity supply to increase from 30% to 50% (IEA, 2016). After Fukushima, under the fourth SEP, this was revised due to uncertainties around nuclear power generation to reduce emissions by 3.8% by 2020 compared to 2005 levels. The fifth SEP aims to decrease electricity generated from fossil fuels from 65% before 2011 to 56% in 2030, adopting further energy saving measures to improve the electricity generation efficiency by 35% and promote hydrogen/energy storage and decentralised electricity systems.

Table 1 demonstrates the projected electricity generation in Japan until 2050, taking into consideration the adjusted SEP targets (IEEJ, 2018). It can be seen that Japan is attempting to decrease dependence on fossil fuels and move towards a more sustainable future. Although there has been a dramatic decrease in nuclear energy generation since 2010, a considerable effort needs to be made to decarbonise the rest of the electricity sector as ~83% of electricity generated came from coal, oil and natural gas in 2015 compared to projections of ~47% by 2050 (IEEJ, 2018).

As part of Japan's fourth SEP from 2014, the METI issued a Strategic Road Map for Hydrogen and Fuel Cells in 2014, which was later revised in 2016. This roadmap describes the goals in each step of hydrogen production, transportation, and storage, and the necessary steps to achieve them through technological challenges and secure economic efficiency (Matsuo et al., 2018; METI, 2017). In phase one,

Table 1
Projected Energy Generation in Japan Between 2015 and 2050 (Source: IEEJ, 2018).

	2015 (TWh) (%)	2030 (TWh) (%)	2040 (TWh) (%)	2050 (TWh) (%)
Coal	343.0 (33.2)	279.0 (25.3)	239.0 (21.8)	197.0 (18.3)
Oil	103.0 (10)	49.0 (4.4)	28.0 (2.6)	97 (0.9)
Natural Gas	410.0 (39.7)	313.0 (28.4)	315.0 (28.7)	302.0 (28.1)
Nuclear	9.4 (0.9)	224.0 (20.3)	215.0 (19.6)	215.0 (20)
Hydro	85.0 (8.2)	92.0 (8.3)	94.0 (8.6)	94.0 (8.8)
Solar PV	36.0 (3.5)	72.0 (6.5)	107.0 (9.8)	131.0 (12.2)
Wind	5.2 (0.5)	18.0 (1.6)	31.0 (2.8)	43.0 (4)
Biomass and Waste	41.0 (4)	55.0 (5)	67.0 (6.1)	82.0 (7.6)
Total	**1,032.6 (100)**	**1,102 (10)**	**1,096 (10)**	**1,073.7 (10)**

the roadmap aims to expand hydrogen use through the expansion of fixed fuel cells and fuel cell vehicles and become a world leader in this technology. Under phase two, they aim to have a full-fledged introduction of hydrogen power generation and establish a large-scale hydrogen supply by the second half of the 2020s. Finally, the third phase will be to establish a CO_2 free hydrogen supply system on a total basis by around 2040 either through the use of carbon capture and storage (CCS) or to produce hydrogen from renewable resources (METI, 2017). The introduction of CCS would allow emissions to be reduced during the transition to low carbon energy generation. CCS is the process where CO_2 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 (Görke et al., 2018). The first commercial CCS project to be fully implemented in Europe was Sleipner in Norway. Since its installation in 1996, this project has captured one million metric tonnes of CO_2 per year from gas production at the Sleipner West Field and has stored these emissions within a geological formation 1,000 m below the seabed (Karimi et al., 2012).

The UK's rail network

The UK's rail network is often perceived as a 'green' mode of transport as compared to the rest of the transport network it only contributed to 2% of total transport emissions, with the equivalent of ~2 $MtCO_2e$ produced in 2016 (DfT, 2019). NR owns and operates the UK's national railway infrastructure as a public body of the UK Government. The network carries ~4.4 million passengers every day on ~22,000 passenger trains and ~11% of the UK's freight (Power et al., 2016). NR operates a total of ~31,000 km of track (including passenger and non-passenger routes), ~30,000 bridges and viaducts as well as thousands of tunnels, signals, and level crossings (ORR, 2017; Wang et al., 2020; Williams Rail Review, 2019). However, most train services are provided by private operators (Bowman, 2015).

Without improvements to the current rail rolling stock, track and platforms, emissions from rail could remain static. To meet emission reduction targets, the UK Government announced in 2018 that diesel-only trains will be phased out by 2040, in favour of alternatively fuelled trains (DEFRA, 2019; Royston et al., 2019). In recent years, electrification of trains and rail infrastructure in the UK has fallen behind many countries with only ~37.9% of passenger railway track electrified, the equivalent of ~6,012 km of ~15,847 km in 2018/19. Therefore, significant upgrading and electrification of the current rail infrastructure will need to be made to meet future travel demand and to reduce GHG emissions from rail.

Urban rail travel plays a key role in many of the UK's major cities by providing public transport services within metropolitan areas (González-Gil et al., 2015). Urban rail is regarded as an ideal solution to increase mobility due to the superior capacity, safety, reliability and environmental performance of the rail service when compared to the private car. However, in terms of environmental emissions, urban rail may lose its competitive edge if it does not reduce its energy usage whilst maintaining or enhancing its service quality and capacity (González-Gil et al., 2014).

To encourage long distance travel, rail needs to remain appealing for consumers in terms of cost and convenience. Introducing high speed rail (such as High Speed 2 (HS2)), brings improvements in track and signalling infrastructure. This in turn enables greater enhancements in efficiency and decreased travel time. HS2 would allow passengers to travel from Birmingham and London (~160 km), currently ~one hour and 21 min, in ~52 min. The UK Government estimates HS2, once complete, will carry up to ~26,000 passengers / hour. To ensure success, cost to the consumer is important (Lalive et al., 2018). There are current plans for further expansions for the HS2 to be implemented with the High Speed 3 (HS3) making improvements to the west-east link from Liverpool in the west to Hull and Newcastle in the east (NIC, 2016). In addition to this, additional plans for a High Speed 4 (HS4) rail link between London to the south west towards Somerset and Devon and Cornwall were announced in 2020.

The UK's energy security and electricity generation

For rail in the UK, there has only recently been an increase in the energy used, both in terms of diesel and electricity. In 2004, rail travel consumed two kilo tonnes oil equivalent (ktoe), which increased 18-fold to 21 ktoe by 2018. To ensure the UK remains on course to achieve its emissions reduction target of net zero by 2050, the Committee on Climate Change (CCC), an independent advisory board to the UK Government, sets five yearly carbon budgets which currently run from 2008 until 2032. The first two carbon budgets ran between 2008 and 2012 and 2013 to 2017 and were achieved with emission reductions of 25% and 31% across their time frames. The UK is currently in the third carbon budget (2018 to 2022) of 2,544 $MtCO_2e$ and on target to outperform this budget (Priestley, 2019). The fourth carbon budget (2023 to 2027) and the fifth carbon budget (2028 to 2032) are 1,950 $MtCO_2e$ and 1,725 $MtCO_2e$ respectively (Priestley, 2019). The UK Government current projections indicate there will be shortfalls within these carbon budgets, and therefore new policies and proposals in the Clean Growth Strategy (2018) are being implemented, with the objective of creating future policy and regulation amendments as the scale of shortfalls becomes clear (BEIS, 2017).

In comparison to Japan, the UK remains a much more energy secure environment due to the diversity of the electricity generation mix since the 1970s and geographical position making it unlikely for natural disasters to affect generation. Although the UK does rely on some fossil fuel use, this has been decreasing rapidly over a ten-year period from 124 TWh in 2008 to 17 TWh by 2018 with all coal power stations to be phased out by 2025 (BEIS, 2018a). During this transition, gas generation infrastructure for electricity generation is expected to provide dispatchable power when renewable energy technologies cannot meet demand. Additionally, the UK still has interconnectors between France and the Netherlands to encourage peak sharing between different time zones and to reduce loading on the UK's National Grid network. To allow further emissions reduction, storage technology should be developed along with the planned increase in renewable energy generation. However, to maintain energy security when solar and wind are not available, dispatchable combined cycle gas turbine (CCGT) power is retained until energy storage is available which is not zero carbon, and installation of CCS should also be considered in the UK for these emissions.

As part of their emissions reduction targets, and while UK law remains a mirror of 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. Table 2 highlights the predicted electricity generation mix based on current policies between 2020 and 2050. The UK Government is committed to achieving this target in the most cost-effective way and expects a shift towards renewable energy with an increase of ~16% from 2020 by 2035 (BEIS, 2019a).

Currently, hydrogen enters the energy generation mix mostly in stand-alone applications as there is no national transmission and distribution network (Fu et al., 2019). The UK Government recently announced a £90 million hydrogen technology fund focussed on supporting low carbon hydrogen production across the energy system, whilst encouraging the private sector to invest in its scaleup and deployment (BEIS, 2020). £70 million will include the production of two of Europe's first ever large-scale production plants with a developing technology to harness offshore wind to power electrolysis and produce hydrogen (BEIS, 2020). The remaining investment will be used to fund projects aimed at cutting household emissions and fossil fuel use. Therefore, although not already in place, technology for hydrogen fuel has been considered and infrastructure is currently under construction.

Methodology

To develop scenarios estimating the CO_2 emissions produced by three differently fuelled trains (DFTs, ETs, HTs) in Japan and the UK, data was obtained from a range of local authority, regional and national databases including the UK Government, National Grid, The Institute Of Energy Economics and METI before being extrapolated to allow projections between 2020 and 2050 (BEIS, 2018b; Ito et al., 2006; National Grid, 2018). This paper does not directly consider the embedded carbon costs of these trains including their construction, decommissioning and the battery costs. An overview of the data used can be seen in Appendix A.

Furthermore, it is important to highlight that this is an overview of all rail types within both countries. In Japan, commuter trains are often classified as metros rather than trains and not often classified within the statistics. UK commuter trains are often included in train statistics although their scheduling and stop frequency make them similar to metro services. Within the UK, the only cities that have a metro are London and Glasgow which are not considered part of the rail network included in this study. This difference between the reporting characteristics of the data used within this study may affect the direct comparability of our outputs. However, the variability is a relatively small proportion of the dataset and is not expected to affect the overall conclusions of this study.

Japan case setting

The estimation of the total number of trains and distance travelled in Japan were based on the projected population changes between 2017 and 2050. During this time frame the Japanese population is expected to decrease by 8.7% from 126.4 million in 2020 to 115.5 million in 2050 (Appendix B). The population change between 2019 and 2020 was used to extrapolate forward the number of trains in use and distance travelled to 2050. This was chosen over the mean growth rate between 1999 and 2020 (the period which data was available for) as Japan's population size is decreasing, so whilst the 2020 growth rate is lower than the mean it is considered to be a more likely approximation of the true population sizes (Appendix C).

For the number of trains, the population size was combined with data taken from the EU-Japan Centre for Industrial Cooperation between 1999 and 2015 to calculate the number of people per train per year by population size. As this trend was approximately horizontal, expected population size was divided by the mean people per train for each year up to 2020. The number of trains thus decreased from 21,538 in 2020 to 19,681 in 2050 (Appendix A).

To estimate the total distance travelled by trains between 2020 and 2050, the total distance travelled by all trains between 1999 and 2015 was sourced from the Handbook of Japan's & World Energy & Economic Statistics by The Energy and Data and Modelling Centre (EDMC, 2017). The yearly increase rate of the average distance per train was calculated using the mean rate of average distance increase per train between 1999 and 2015, as it was approximately linear, and used to project distance travelled up to 2050. As described above, the number of trains was calculated in relation to population size and therefore the distance values used in this study are indirectly related to population size. This shows an increase in distance from $8.80x10^9$ km in 2020 to $1.05x10^{10}$ km in 2050 (Appendix A).

To estimate the carbon intensity for electricity generation for both ET and HTs, the electricity generation mix between 2020 and 2050 was calculated using Japan's 2050 Low Carbon Navigator (IGES, 2010). These values focussed on electricity generated in Japan assuming an 80% reduction in GHG emissions and therefore is the most comparable to the UK's two degree scenario (Appendix C).

UK case setting

For the UK, the Transport Energy and Air Pollution Model (TEAM-UK) was used to estimate the projected number of trains and distance travelled between 2020 and 2050. This is an updated version of the UK Transport Carbon Model (UKTCM) (Brand et al., 2012, 2019, 2020). TEAM-UK is a disaggregated, bottom-up modelling framework of the UK transport-energy-environment system, built around a set of exogenous scenarios of socio-economic, socio-technical and political developments (Brand et al., 2019). Projections from TEAM-UK for trains came in four types: light, regional (i.e. commuter), national and high speed, which were combined to give an overview of the rail system in the UK (Brand and Anable, 2019).

Using TEAM-UK, between 2020 and 2050 the total number of trains is expected to remain relatively constant increasing by 0.9% from 6,394 trains to 6,454 trains. The total distance travelled by these trains' increases by 10.5% from 533,311,266 km to 589,249,435 km. Best case scenario data was used for the carbon intensity of electricity generation. This was obtained from the National Grid two degrees scenario (National Grid, 2018). The scenario reflects the UK adhering to the global ambition to restrict global temperature rise to below the 2 $^{\circ}$C above pre-industrial levels, as set out in the Paris Agreement. This scenario provides large-scale solutions with consumers expected to choose

Table 2
Projected UK electricity generation mix based on current policy between 2020and 2035 (). Source: BEIS 2019a

	The UK Electricity Generation Mix (TWh) (%)			
	2020	2025	2030	2035
Coal	1 (0)	0 (0)	0 (0)	0 (0)
Coal and natural gas CCS	0 (0)	0 (0)	0 (0)	0 (0)
Oil	0 (0)	0 (0)	0 (0)	0 (0)
Natural gas	100.5 (34)	73.5 (26)	74.8 (25)	51.6 (17)
Nuclear	59.2 (20)	40.5 (14)	63.7 (21)	57.6 (19)
Other Thermal	0 (0)	0 (0)	0 (0)	0 (0)
Renewables	134.7 (45)	170.4 (59)	159.4 (53)	182.9 (61)
Storage	3.2 (1)	3.6 (1)	5.0 (2)	7.8 (3)
Total electricity supplied (gross)	298.6 (100)	288.0 (100)	303.0 (100)	300.0 (100)

electric and hydrogen (H_2) technologies for heat and transport options to meet the 2050 targets. This scenario was chosen as it will allow policy-makers to better understand the maximum level of emissions that could be emitted for the UK to meet their global and national agreements.

Estimating operating emissions from diesel fuelled trains

To estimate the total CO_2 emissions produced for DFTs in Japan and the UK, **Equation 1** was used:

Equation 1

$$Emissions_{Trains} = N * D * C$$

Where, N = total number of trains, D = distance travelled (kilometres), T = train by fuel type (in this case DFTs) and C = grams of carbon dioxide per kilometre travelled by train ($gCO_2\ km^{-1}$). Data units are converted into $MtCO_2$.

For the UK, 2,870 $gCO_2\ km^{-1}$ was used which was a conservative approach for the grams of CO_2 produced every kilometre travelled (C) (Pridmore, 2009). To take into consideration technological improvements of diesel trains, 10 $gCO_2\ km^{-1}$ was deducted every ten-year time step. Emissions per distance data was not available in the literature for Japan, therefore the total level of emissions produced was calculated by multiplying the litres of diesel per kilometre (26.40 L km^{-1}) by the level of carbon produced per kilogram of diesel fuel (2.63 $kgCO_2$), this gave an overall value of 6,954 $gCO_2\ km^{-1}$ (Sims et al., 2006). It is important to note that currently only 1% of trains within Japan are diesel so this assumption may not represent the average size and weight of all trains (ERIA, 2019). The differences between UK and Japan efficiency values are largely thought to be due to average carriage numbers,this is accounted for in the number of trains and population related estimates.

Electric and hydrogen train emissions

To estimate the total level of emissions produced from a full rolling stock of electric and hydrogen passenger trains in Japan and the UK, **Equation 2** was used:

Equation 2

$$Emissions_T = (((N * D) * (G_T * P_T)) * I) * CI$$

Where, G = annual train energy consumption ($kWh\ km^{-1}$), P = correctional factor for fuel cell efficiencies dependent upon source of power, I = correctional factor for grid and generation inefficiencies and CI = carbon intensity of electricity generation ($gCO_2\ kWh^{-1}$), T = power train type (electric or hydrogen). Data units are converted to $MtCO_2$.

For both Japan and the UK, G represents the energy consumption per kilometre by the given train power source, with the average electric train energy consumption (G) ranging between 3.5 and 5.5 kWh km^{-1} (Gattusoa and Restuccia, 2014). Implementing a worst case scenario approach, the maximum annual train energy consumption was chosen at 5.5 kWh km^{-1} for both countries. These values were taken from an energy consumption modelling paper (Jong and Chang, 2005) as no country specific data is available. The method described here is likely sensitive to this parameter depending on country as energy consumption values are influenced by the mass of trains and the route speed and topographical profiles.

For Japan, HTs were given a value of 7.1 kWh km^{-1}. This value was chosen as it is the wheel-to-wheel value for fuel cell electric trains by 2030 for east Asia (ERIA, 2019). For HTs, the consumption value for the UK was 10 kWh km^{-1} (Progressive Energy Ltd, 2019). This value was likely higher as there are limited HTs currently in use in Europe. Although this value may decrease over time resulting in trains becoming more energy efficient, HTs are still considered a relatively new technology and there is limited literature on future hydrogen consumption values. This difference in the level of emissions produced per train per year between countries is influenced by the longer distances travelled and that trains within Japan tend to have a larger number of carriages compared to UK trains.

For both countries, electric power transmission and distribution losses (I) (as a percentage of output) was estimated from The World Bank. This gave the UK a value of 1.08 and Japan a value of 1.04 (The World Bank, 2018).

Hydrogen was assumed to be produced from electrolysis, as this is the method that can most readily utilise a variety of renewable energy inputs. For HTs, the grid inefficiency of 1.08 for the UK and 1.04 for Japan was multiplied by an additional 1.72 inefficiency factor accounting for hydrogen generation electricity requirements, assuming H_2 was generated from electrolysis. For every 1 GJ of H_2 to be produced, 479 kWh of electricity needs to be generated from the energy source (specific sources or general market can be used in the estimation) (Fernández-Dacosta et al., 2019). The 1 GJ of H_2 was converted to kWh by dividing this by 3,600, implying 277 kWh equivalent of H_2 had been produced (Fernández-Dacosta et al., 2019). This therefore gave an inefficiency correction factor of 1.72 and an overall inefficiency value (I) of 1.79 for Japan and 1.86 for the UK. Although power distribution losses are expected to improve through technological improvements, limited information quantifying this is currently available. This has resulted in current and future years being run with the same correctional factor for both Japan and the UK, therefore energy required, and emissions produced by electric trains in 2050 may be overestimated.

Results

The results of this analysis compares the emission levels of DFTs, ETs and HTs for Japan (Section 3.1) and the UK (Section 3.2). Section 3.3 compares the results for DFTs, ETs and HTs in both countries, focussing on the required energy and subsequent emissions per train together with the cumulative emission over the time frame.

Emissions from diesel fuelled, electric and hydrogen trains in Japan

Fig. 1 demonstrates the projected CO_2 emissions if all trains were either 100% DFTs, 100% ETs or 100% HTs in Japan between 2020 and 2050.

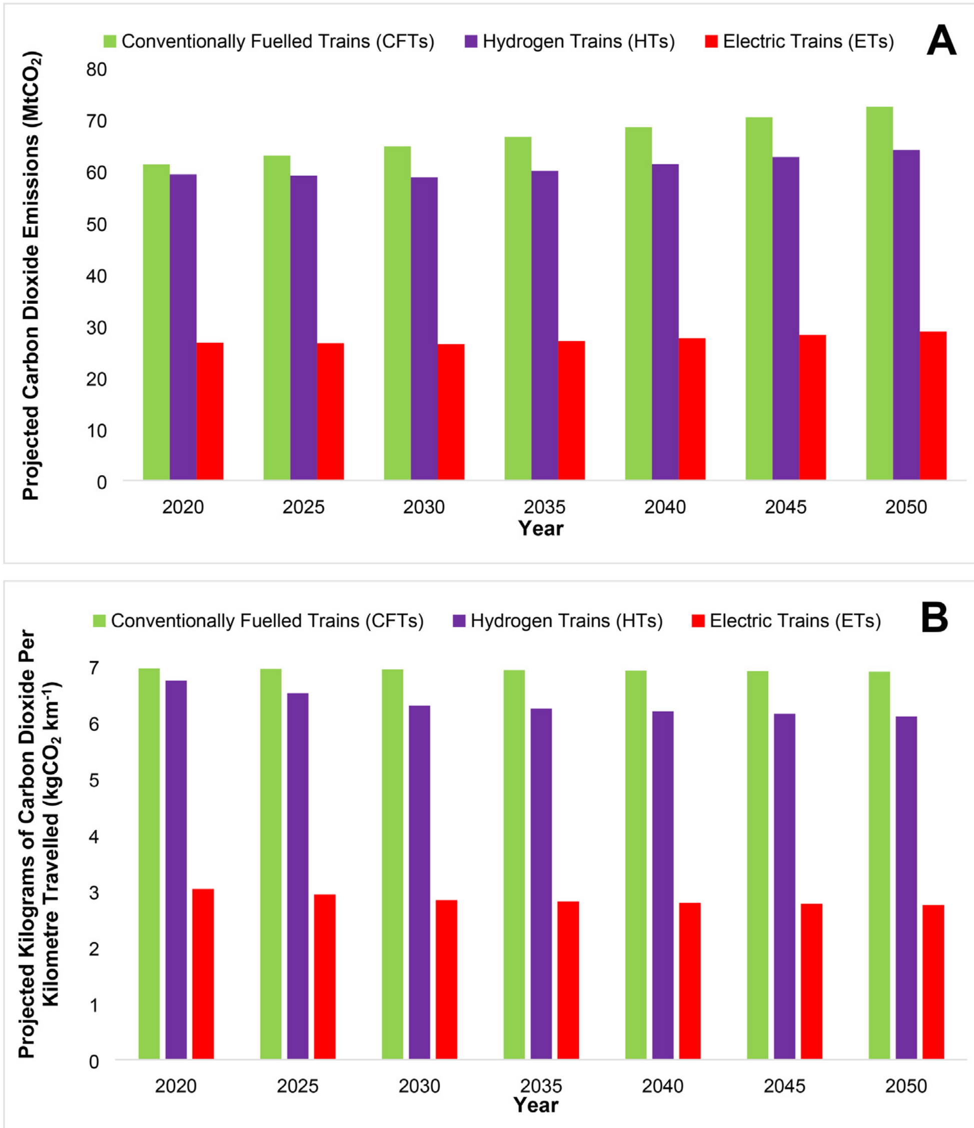

Fig. 1. (A) Projects the total carbon dioxide emissions from diesel fuelled trains, hydrogen trains and electric trains in Japan between 2020 and 2050 in five-year increments. (B) Projects the kilograms of carbon dioxide per kilometre travelled by train type for Japan between 2020 and 2050 in five-year increments.

Results from Fig. 1**(A)** indicate that 100% DFTs within this period exhibit the largest increase in the level of emissions by 18% from 61.2 $MtCO_2$ to 72.3 $MtCO_2$ within the time frame. This remains a hypothetical scenario as only ~1% of trains within Japan are diesel. Whilst the likelihood of large-scale DFTs is very low, it is interesting to note that due to the high carbon intensity of Japan's energy generation, emissions from HTs are not dissimilar than if all trains were DFTs. If all rail was diesel, results indicate that even with technological advances in terms of the $gCO_2\ km^{-1}$, emissions increased. Under Fig. 1**(B)**, results indicated that 100% DFTs produced the highest level of emissions at 7.0 $kgCO_2\ km^{-1}$ in 2020 decreasing by 1.4% to 6.9 $kgCO_2\ km^{-1}$ by 2050.

Under Fig. 1**(A)**, HTs emissions increase by 8% from 59.3 $MtCO_2$ to 64.0 $MtCO_2$ between 2020 and 2050. Furthermore, under Fig. 1**(B)**, results indicated that 100% HTs saw the largest decrease in emissions produced per kilometre travelled, decreasing by 9% from 6.7 $kgCO_2\ km^{-1}$ in 2020 to 6.1 $kgCO_2\ km^{-1}$ by 2050. Along with an increase in distance travelled, this is a result of a high kilowatt hours per kilometre due to the additional energy required for additional stages in H_2 generation. Furthermore, there was also additional energy lost during generation which likely contributed to higher levels of emissions.

If 100% of trains were electric during the time frame, under Fig. 1 **(A)**, using the two degree equivalent electricity generation scenario to meet the Paris Agreement, emissions are still expected to increase by 8% from 26.7 $MtCO_2$ to 28.8 $MtCO_2$ within the thirty-year time frame. This increase in emissions is likely due to the increase in projected distance travelled per train, which was highlighted under Fig. 1**(B)**, as emissions show a 6.7% decrease from 3.0 $kgCO_2\ km^{-1}$ to 2.8 $kgCO_2\ km^{-1}$ within the time frame. In addition, results highlight that if the remaining 1% of non-electric trains were converted to H_2, the reduction in emissions would be minimal. Therefore, if Japan wants to successfully meet their Paris Agreement targets, in spite of the almost total electrification of the rail system, it needs to decarbonise the train electricity supply.

Emissions from electric and hydrogen trains in the UK

Fig. 2 highlights the projected CO_2 emissions from 100% DFTs, 100% ETs and 100% HTs in the UK between 2020 and 2050 and the grams of CO_2 per kilometre travelled for each train type. Results from Fig. 2**(A)** highlight that with 100% DFTs emissions are expected to increase by 8.5% from 1.5 $MtCO_2$ to 1.7 $MtCO_2$. Results from Fig. 2

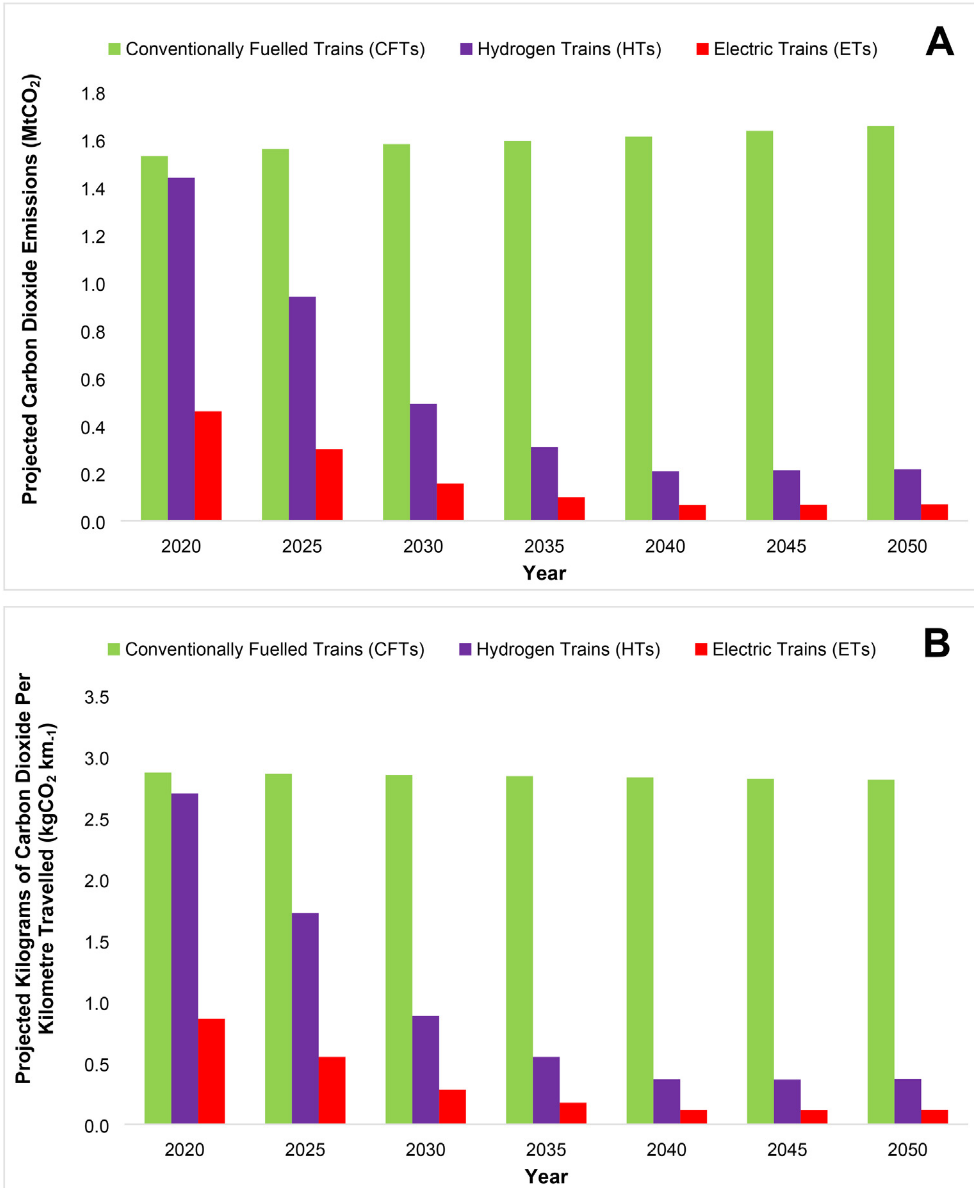

Fig. 2. (A) Projects the total carbon dioxide emissions from diesel fuelled trains, hydrogen trains and electric trains in the UK between 2020 and 2050 in five-year increments. (B) Projects the kilograms of carbon dioxide per kilometre travelled by train type in the UK between 2020 and 2050 in five-year increments.

(B) indicate that emissions per kilometre travelled by DFTs decreased by 3.4% from 2.9 $kgCO_2$ km^{-1} in 2020 to 2.8 $kgCO_2$ km^{-1} by 2050. Therefore, this overall increase in emission levels indicates technological advances will not offset the increase in the number of trains and the distanced travelled by trains in terms of emissions.

For 100% HTs, under Fig. 2**(A)** emissions decreased by 85% from 1.44 $MtCO_2$ to 0.22 $MtCO_2$ non-linearly across the time frame. Under Fig. 2**(A)** results indicated that 100% HTs saw a decrease in emissions produced per kilometre travelled, decreasing by 85% from 2.7 $kgCO_2$ km^{-1} in 2020 to 0.4 $kgCO_2$ km^{-1} by 2050.

Although 100% ETs did not see the largest decrease in emissions, they produced the overall lowest level of emissions. Under Fig. 2**(A)**, emissions decreased by 85% from 0.46 $MtCO_2$ in 2020 to 0.07 $MtCO_2$ by 2050. Under Fig. 2**(B)**, emissions per kilometre travelled saw the largest decreased by 89% from 0.9 $kgCO_2$ km^{-1} to 0.1 $kgCO_2$ km^{-1} within the time frame.

This decrease in the level of emissions from both HTs and ETs is due to the rapid decarbonisation of electricity generation. It also demonstrates the impact of electricity generation decarbonisation on transport decarbonisation.

Comparison of train emissions

Results in Sections 3.1 and 3.2 highlight that the level of emissions from all rail types in Japan are expected to increase, whereas for the UK, only the expected emissions from 100% DFTs will increase. For both countries it was clear that 100% HTs produced the second lowest level of emissions followed by ETs producing the lowest level of emissions. To get a more direct comparison between countries, we analysed the energy required per train, emissions per train and the cumulative emissions of DFTs, ETs and HTs for both countries between 2020 and 2050.

Energy required per train Japan and the UK

Table 3 highlights the level of emissions produced per train for 100% DFTs, HTs and ETs for Japan and the UK between 2020 and 2050.

Table 3
Carbon dioxide emissions produced per train in Japan and the UK between 2020 and 2050.

	Japan (tCO_2 per train per year)			The UK (tCO_2 per train per year)		
	Diesel Fuelled Trains	Electric Trains	Hydrogen Trains	Diesel Fuelled Trains	Electric Trains	Hydrogen Trains
2020	2,840.6	1,238.3	2,751.4	239.4	71.9	225.1
2025	2,965.2	1,251.8	2,781.3	243.3	46.8	146.7
2030	3,095.4	1,263.9	2,808.3	245.8	24.4	76.4
2035	3,231.2	1,310.6	2,912.1	247.5	15.3	48.0
2040	3,373.0	1,359.0	3,019.4	250.0	10.3	32.4
2045	3,521.0	1,410.4	3,133.8	253.6	10.5	32.8
2050	3,675.5	1,453.0	3,252.3	256.6	10.7	33.6

For Japan, results indicate that for all train fuel types, the level of emissions produced per train per year increased. The largest increase was for DFTs which saw an increase of 29% over the time frame increasing from 2,840.6 tCO_2 per train per year to 3,675.5 tCO_2 per train per year. HTs produced the second largest increase by 18% whilst ETs increased by 17% between 2020 and 2050.

For the UK, DFTs increased by 7.2% from 239.4 tCO_2 per train per year to 256.6 tCO_2 per train per year. Both HTs and ETs decreased the level of emissions produced per train by 85% and 85.1% respectively over the thirty-year time frame. This decrease in the level of emissions is due to the decarbonisation of energy generation as although there is likely to be an increase in the number of trains and distance travelled, emission reductions outweigh predicted usage increases.

The emissions per train per year in Japan increased within the time frame for all train types. Although there is an expected decrease in the total number of trains, due to a decrease in population size, there is an expected increase in distance travelled by 2,511,920,000 km over the 30-year time frame. This increase in the distance travelled is likely due to the extensive rail network already in place. As the UK begins to shift towards low carbon public transport, the total number of trains and the distance travelled is likely to increase. However, due to technological advances and a rapid decarbonisation of electricity generation, the level of emissions from all train types is likely to decrease over the time frame.

The differences in emission levels between these two countries could largely be influenced by the differences between UK and Japan's average carriage numbers, which has been accounted for in the number of trains and population related estimates. Furthermore, as DFTs only represent a small proportion of trains, with ~1% of trains expected to be DFTs by 2040 (ERIA, 2019), the emission levels would be expected to be higher as most Japanese trains have multiple train carriages (Shinkansen trains have ~16 carriages (Hood, 2006)). In comparison, the UK normally has around seven carriages per train which often leads to overcrowding and higher emission levels. However, the Railway Delivery Group has revealed an increase of a further 1,300 carriages by 2021 to reduce overcrowding (Global Railway Review, 2018). Therefore, emission levels would be expected to be higher for Japan as there is a higher number of carriages comparatively.

Cumulative emissions from diesel fuelled, electric and hydrogen trains in Japan and the UK

Assuming a linear relationship between the five-year intervals, cumulative emissions under all three scenarios were estimated based on the five-year time step data available as seen in Table 4.

The cumulative emissions of DFTs was higher than ETs and HTs in both Japan and the UK. Both ETs and HTs are expected to see technological advances so other factors including the projected number of trains and distance travelled can influence cumulative emission levels (see Appendix A). Japan is expected to emit 2,150.5 $MtCO_2$ between 2020 and 2050, which would be a worst case scenario as only a limited number of trains in Japan are currently fuelled by diesel. For the UK,

Table 4
Comparison of cumulative emissions of 100% diesel fuelled, electric trains and hydrogen trains in Japan and the UK between 2020 and 2050.

	Japan ($MtCO_2$)	The UK ($MtCO_2$)
Diesel Fuelled Trains	2,150.5	49.5
Electric Trains	879.7	5.0
Hydrogen Trains	1,954.6	15.8

49.5 $MtCO_2$ is expected to be emitted within the time frame, which is due to the increased travel distance and number of trains.

Cumulative emissions highlighted that ETs in both countries produced the lowest level of emissions between 2020 and 2050. It is projected that for 100% ETs, Japan would emit 879.7 $MtCO_2$ over the 30-year period. This level of emissions is due to the electricity generation mix remaining relatively carbon intensive over the time frame. Within the same time frame the UK is expected to emit 5 $MtCO_2$ which is due to the UK being projected to transition to almost no fossil fuel generation within the time frame.

HTs produced the second highest level of cumulative emissions for both countries, emitting 1,954.6 $MtCO_2$ and 15.8 $MtCO_2$ in Japan and the UK respectively. This is due to the additional stages in H_2 generation leading to potential energy losses, the influence of the energy generation mixes as well as the projected number of trains and distance travelled.

However, realistically, since only ~1% of trains are DFTs in Japan it is more likely that there will be a mixture of ETs and HTs in Japan going forward to 2050. Assuming a split of 50:50 ETs and HTs, it could be assumed that cumulative emissions for Japan could be 1,417.2 $MtCO_2$. This number is likely to be lower as ETs are favoured in Japan. Alternatively, in the UK, there is a greater share of DFTs than low carbon alternatives, therefore cumulative emission levels are likely to remain higher, even with new policy phasing out diesel-only trains by 2040. Therefore a 50:50 split of ETs and HTs in the UK would be a best case scenario at this stage with cumulative emissions of 10.4 $MtCO_2$, a value much likely higher as ETs are phased into the train network.

Energy generation for fully electric and hydrogen trains in Japan and the UK

Table 5 highlights the projected energy required if all trains were either electric or H_2 in Japan and the UK between 2020 and 2050. Within this time frame, both countries experience an increase in energy demand for both ETs and HTs. Overall, results indicate that for both countries, more energy would be required to be generated for HTs. This is due to the additional steps required to generate H_2.

In Japan, ETs would need an energy generation increase of 24.9% from 514.7 GWh to 642.7 GWh within the time frame. HTs would need an energy generation 24.9% increase from 2020 to 2050 from 664.4 GWh to 829.7 GWh. In the UK, ETs would need an energy generation increase of 10.4% from 31.7 GWh to 35.0 GWh within the time frame.

Table 5
Projected energy required to fuel electric and hydrogen trains in Japan and the UK between 2020 and 2050.

	Japan (GWh)		UK (GWh)	
	Electric Trains	Hydrogen Trains	Electric Trains	Hydrogen Trains
2020	514.7	664.4	31.7	57.6
2025	536.0	692.0	32.4	58.9
2030	557.4	719.5	32.9	59.9
2035	578.7	747.0	33.3	60.6
2040	600.0	774.6	33.8	61.5
2045	621.4	802.1	34.5	62.7
2050	642.7	829.7	35.0	63.6

HTs would need an increase energy generation of 10.4% from 57.6 GWh to 63.6 GWh.

Taking into consideration the current state of train electrification in Japan, an additional 5.1 GWh of energy for ETs would be required in 2020 to power the 1% of trains that are not currently expected to be electric by 2040. By 2050, an additional 1.3 GWh of electricity would be required to meet this demand. For HTs, an additional 6.6 GWh of electricity would be required in 2020, with an additional 1.7 GWh by 2050 to meet the 1% demand.

Discussion

Results from this analysis indicate that between 2020 and 2050, in both countries, DFTs produced the highest level of emissions even with technological advances. Overall ETs produced the lowest total and cumulative level of emissions in both countries, followed by HTs. This study indicates that both countries need to take a different approach to reduce their rail emissions. As Japan has already electrified a majority of their rail lines, decarbonising of the electricity generation mix is required to see a reduction in emissions. Alternatively, the UK has focussed on decarbonising electricity generation but has been slow with electric uptake and has only recently brought in plans to ban the sale of diesel-only trains to 2040, while the rail network is not currently advanced in terms of electric rail lines to support ETs. As trains have a life expectancy of ~20 years, any trains commissioned in 2040 could still be in use by 2060 which could be problematic when trying to meet Paris Agreement targets (Zenith et al., 2019). From the 1970s, trains in the UK were designed as a cost-effective solution to meet demands, however almost thirty years later some are still being used. This highlights a key difference between Japan and the UK, as Japan has spent significant money investing into their rail network and has an almost entirely electric rail network unlike the UK. Therefore although Japan produces higher levels of emissions than the UK, emission levels are significantly lower than if Japan had continued to use DFTs. If the UK wants to reduce emissions, significant investment needs to be made to decarbonise the trains themselves through the introduction of ETs as well as low carbon energy generation investments.

In this analysis, we have focused on the rail sectors in Japan and the UK because the UK is advanced in decarbonising their energy sector but slow at transitioning their rail network to electric, whereas Japan is in the opposite situation. This contrast highlights the need in both countries to improve the rail network if both countries are going to meet their national targets as part of the Paris Agreement. Moreover, analysing the impact for passenger rail travel indicates that both countries need to reduce emissions significantly further, with the need for further research to also consider freight as both passenger and freight demands continue to grow (Li, 2019). Freight transport is a complex network and is interrelated with production, trade, and consumption activities, and involves more stakeholders than passenger transportation (Li and Zhang, 2020). Rail freight remains more environmentally friendly than road freight therefore transfer from road to rail can reduce emission levels, however the extent of this reduction requires additional research (Lin et al., 2017).

Decarbonisation of electricity generation

The UK has begun transitioning towards a higher percentage of renewable electricity generation technology within its electricity mix and is on track to eradicate coal before 2025. The UK has a relatively secure and diverse energy mix but will also have to overcome obstacles to meet net zero emissions by 2050. For example, Scotland produced ~42.8% of their energy from nuclear power stations in 2016, however, (The Scottish Government, 2017) has decided to phase out the use of nuclear energy after the remaining power stations are decommissioned in 2025 and 2030. Even with a focus on renewable energy, Scotland's GHG emissions increased in 2018 compared to 2017, as one nuclear reactor was offline for an extended period of time which resulted in Peterhead gas plant being used for a sustained period of time. Therefore, this energy gap will need to be filled from low carbon energy generation to ensure energy demand is met. The installation of additional renewable energy generation will be required UK wide to be able to meet the additional energy demands, however one issue the UK will face is where to locate the land intensive renewable solar and wind infrastructure. There is limited land available and it may have to rely on imports and dispatchable gas generation during times of peak demand or low renewable availability. However, for imports, knowledge of where and how the electricity is generated, and in what country, is required to quantify the emissions intensity of the imported electricity. Only by having a system in place that either does not rely on imports or ensures that electricity imported is generated from renewable or nuclear energy will low emissions be guaranteed.

The introduction of more widespread CCS could be implemented to limit the GHG emissions produced from fossil fuels during this shift to renewables. This process has already been introduced in Japan in 2016 in a demonstration project called Tomakomai. This project captured 0.1 Mt/year of CO_2 from an oil refinery (Tanaka et al., 2014). Although this is small scale, increased utilisation of CCS alongside their gas-fired and other fossil-fuelled power stations will help to negate emissions produced and allow Japan to work towards their Paris Agreement targets. However, although this CCS project has been introduced successfully costs remain high and Japan has limited domestic potential for geological storage, except for those in underground aquifers (Akimoto et al., 2007; Matsuo et al., 2018). Therefore, even if cost is significantly reduced, widespread introduction of CCS in Japan will be limited by the availability of underground aquifers for storage.

Alternatively, the UK remains one of the best locations for CCS implementation as there are appropriate carbon storage sites (depleted oil and gas reservoirs and saline aquifers) with appropriate offshore infrastructure (BEIS, 2019b). The ACORN project at the St Fergus Gas Terminal in Scotland is installing a CCS system at minimal capital costs to capture, transport and storage CO_2 produced by the gas terminal and a H_2 methane reforming plant by ~2023 (Alcalde et al., 2019). The H_2 will be injected into the gas grid. The ACORN project will reuse current infrastructure, including existing oil and gas pipelines which are now redundant, prior to decommissioning, to minimise environmental and financial costs (Cooper and Hammond, 2018). It has been projected that the ACORN project is expected to capture ~200,000 tonnes of CO_2 per year once up and running from 2022 (Pale Blue Dot, 2017). Through Japan and the UK's separate initiatives, both examples highlight the importance of low carbon energy generation and the potential of small scale demonstrations to kick start the CCS industry to reduce emissions from fossil fuels.

Electric rail

ETs produced the lowest level of CO_2 emissions in both countries. However, in regional areas, electrifying rail lines may require either replacing existing lines causing disruptions or installing overhead lines to supply electricity as battery powered trains are not considered viable due to added weight. Fig. 1**(B) and 2(B)** indicate that overall distance travelled is a primary driver of total emissions. This highlights that a key target for policy makers when considering transport policies is to focus on reducing total passenger kilometres. The total population mileage is greater reduced by using mass transit systems as passenger capacities are higher and therefore require less transport units than private transport (i.e. the average regional train in the UK caries 447 people, which would require the equivalent of 112 private cars assuming four people per car (Brand et al., 2019; Logan et al., 2020b). This requires a large infrastructure investment and disruption to services during installation particularly on single line track sections. Within a rural setting, HTs may be a better option as they avoid the electricity supply installation cost and are able to travel long distances between fuelling. In addition sites for H_2 generation may be located in remoter rural settings close to renewable power generation. Maximising early transitions to low carbon rail where appropriate is necessary for the UK to meet it emission targets.

Even with predominantly electrified rail, to ensure that emissions remain as low as possible and for both counties to meet their Paris Agreement targets, both countries will need to decarbonise their electricity generation mix. Results highlight that under the best case scenario, renewable or nuclear electricity generation will need to become a priority, as when both countries had a higher share of renewables and nuclear, emission levels were lower. Without decarbonising electricity generation, the environmental benefits of low carbon rail will be diminished. Since the Fukushima incident in 2011, Japan has shifted away from nuclear energy and has been importing more fossil fuels, as this energy gap is considered difficult to meet from renewables alone (Aruga, 2020). For Japanese low carbon rail to have a significant impact on emission reductions, further investment and integration of renewable electricity generation within Japan needs to be made. With targets set under the fifth SEP and the Strategic Roadmap for Hydrogen and Fuel Cells, Japan will phase out fossil fuels towards 2050 to meet their emission reduction goals. Through this expansion, energy insecurity will also decrease as their electricity mix will also be diversified, thus reducing potential blackouts. Although the cost of renewables has decreased, especially for solar PV and wind, a major barrier is the variability and intermittency of energy generation, therefore if coupled with other renewables such as wind, storing energy for peak times will be important (Matsuo et al., 2018).

Hydrogen rail

If both countries were to introduce HTs, H_2 would need to be generated from electrolysis if emissions are to be less substantially less than the predictions for DFTs (Logan et al., 2020b). Considering realistic development, H_2 generated through electrolysis is limited to small scale operations and is not always possible or economical. Therefore, one solution is to generate H_2 through steam methane reform using natural gas or coal gasification with CCS. Combining this process with CCS will help reduce GHG emissions produced through larger scale H_2 projects. For example, to support the H_2 market in Japan, Woodside Petroleum plan to use their North West Liquefied Natural Gas plant off the coast of Western Australia to convert gas into liquid H_2 with CCS and export this to Japan. This process would result in Australia producing the H_2 as the production process requires a significant amount of energy. However, the plant itself is currently fuelled by gas and is currently making the switch towards solar energy and batteries in order to ensure these environmental benefits are not diminished by the H_2 generation process. This process will require significant infrastructure investment on both ends of this process.

Although H_2 generation currently emits varying level of emissions dependent on the method of generation, this is not to say that electrolysis will not be developed in the future, with the potential to scale up through investment and reduce these emission levels. However, like most technologies, the infrastructure will take time to develop given the capital costs needed and it will only be low carbon with abundant renewable or nuclear energy used for the process. This is more likely to happen in the UK than Japan with current generation trends in both countries. Japan is currently struggling to decarbonise its electricity after nuclear power was shut down after the tsunami, whereas even at 25% wind generation penetration, the UK frequently has excess wind power that is 'switched off' to avoid overloading the network. By the end of 2019, there were ~177 hydrogen fuelling stations in Europe and ~114 in Japan with further plans for expansion (LBST, 2020). Despite an increase in the number of H_2 fuelling stations, demand remains low and it is not always economically feasible to build large-scale H_2 fuelling stations.

By adapting existing H_2 storage systems, associated costs could be kept at a minimum for rail travel (Chan et al., 2013). However, large-scale material-based H_2 storage has basic technological challenges that still need to be overcome, and further scientific research is required before extensive commercial deployment can be fully utilised (Chanchetti et al., 2020). With this said, to reduce variable and intermittent renewable energy sources, converting electricity to H_2 represents a viable pathway to reduce the impacts of renewable electricity on the electricity grid (Gallardo et al., 2020; Lew et al., 2010).

In recent years, Japan has been pushing a H_2 economy with the introduction of Japan's Hydrogen and Fuel Cell Roadmap (Khan et al., 2021). This strategy aims for an annual production of ~300,000 tonnes of H_2 by 2030, at a cost of \$0.28/Nm^3 and from \$0.19/Nm^3 thereafter. Longer term, this strategy aims to produce between 5 and 10 million tonnes of hydrogen by ~2050 (Trencher et al., 2020). In 2019, the Fuel Cell and Hydrogen Energy Association (FCHEA) highlighted the projects that Japan had been undertaking concerning H_2 fuel cell development (Thomas et al., 2020). Their report demonstrated that these fuel cells can act as a power source for several modes of transport, which will allow Japan to diversify and strengthen their national energy infrastructure (Thomas et al., 2020). This has the potential to promote HTs as a novel alternative to ETs in the future. However, Japan's Hydrogen and Fuel Cell Roadmap does not focus on transport alone, with the need for H_2 outside the transport sectors including heat and industry to ensure demands are fully met (Chehade et al., 2019; Gallardo et al., 2020; Schiebahn et al., 2015; Trencher et al., 2020).

Challenges for widespread integration of low carbon rail

The relative cost of rail travel remains high (in the UK) driven by the increased capital expenditure (CAPEX) cost of upgrading rail networks, traction and rolling stock, which has been long delayed, and high operating costs of outdated equipment. This has discouraged rail travel in the UK. However, if the operating costs can be reduced and reliability increased by new equipment, lower fares may encourage rail use. HTs are currently ~50% more expensive than DFTs, however their projected operating costs are dependent on potentially lower-fuel costs associated with cheaper H_2 production and on fuel cells improving efficiency as is currently the trend (Hart et al., 2016; Staffell et al., 2019). The current cost of a new hydrogen refuelling station is ~JPY 350 million (~EUR 2.8 million), which is much higher than the cost for an oil fuel station of JPY 100 million (~EUR 800,000) (Jensterle et al., 2019). This also does not take into consideration where H_2 will be stored before the HTs will be fuelled. This has left a 'chicken and egg' problem as Japan's uncertainty about H_2 demand has a negative effect on infrastructure investment and in turn the availability of refuelling stations which is fundamental in securing HT uptake, however with only one percent of Japanese railways requiring conversion to either ET or HT this is a small issue. In the UK however, with a large part of the rail network to be decarbonised, the trade-off between electrifying lines and the availability of distributed H_2 from abundant renewable electricity will be an important consideration in the technology and investment choice. In addition, although there is a higher start-up investment cost for both ETs and HTs over DFTs, long-term lower running costs and environmental benefits will produce an overall economic benefit.

Japan's rail service is known globally for its fast, safe, reliable, punctual and affordable service and it remains an attractive transport option for business and pleasure travel (Bugalia et al., 2019; Sato et al., 2018). If there are disruptions to train schedules for example from accidents, natural disasters, engine troubles etc. a series of modifications to the train schedule are made and passengers are kept up to date (Sato et al., 2018). This reputation of rail travel has been built up over the past several decades which has resulted in this method of transport being widely used in Japan. Japan has actively tried to encourage tourists to travel by rail instead of personal vehicle by allowing them to purchase discounted train passes on specific trains between most major cities for specific time frames (for example, seven days, 14 days or one month passes etc.). Although this is a short period of time, repeated use of a service like this may encourage individuals to use public transport when they return to their home country. Furthermore, Japanese users are able to use a 'top-up' smart card with over 30 railway operators accepting smart cards in various regions in Japan (similar to London's Oyster Card), increasing the convenience for customers (Kusakabe et al., 2010). This also has the added benefits of train providers collecting transactional data to better understand how passengers use public transport which can be used to improve current routes and to ensure passenger demands are met with enough train frequency (Kusakabe et al., 2010). In November 2016, this resulted in ~1,237 km of rail lines being closed as they could not be sustained only through the revenues of the business and demand was not high enough (Kurosaki and Alexandersson, 2018).

Train services in the UK are not kept to the same standards as Japan and are often late or delayed or travellers face overcrowding on both platforms and on the train during peak travel times, with 55% of passengers in 2020 eligible to claim compensation for a delay (an increase of 10% from the previous year) (DfT, 2020). Of this compensation, the proportion of passengers claiming compensation for a delay of 30 min of more increased by 46% in 2020 (DfT, 2020). Whereas in Japan, the average delay for JR-East remained between 0.3 and 0.5 min per train between 1999 and 2006 (Bugalia et al., 2019; Oliveira et al., 2019). In the UK, delays to service and the low costs of other alternative transport methods, such as low cost internal flights or driving, often make trains the least attractive option. Therefore, if the UK wants to encourage greater rail use (and assuming sufficient rolling stock can be made available) adapting to Japanese standards of a fast, reliable and lower cost rail service is advisable. With the introduction of HS2, although individuals may be able to get to their destinations quicker and easier from city centre to city centre, if the cost to the consumer is not competitive with other modes, it may not be the most attractive option. Therefore, travellers may need to decide whether cost or convenience may be the bigger influence when deciding what transport option to take with travel demand management initiatives needing introducted to actively encourage sustainable travel options (Lalive et al., 2018; Logan et al., 2020d).

Limitations of this study

For the purposes of this analysis, we have focused on the tailpipe emissions of rail, however, decision making bodies have begun to look at life cycle analysis (LCA) methodologies for critical inputs related to transport fuels (Chester and Horvath, 2009). However, LCAs are generally limited in use with comparisons to other countries hindered due to data restrictions. Therefore, for the purposes of this research, an operating emissions model was used. This methodology considered fewer variables with a more focussed approach which has the potential to be used for comparison on a broader range of countries. The model allows for easy substitution of other train fuel types, directly into the model, with different train type percentages, number of trains and distances travelled easy to adjust. Although the model quantitatively underrepresents the true costs and subsequent total emission targets being met, consistent values are used for analysis within the model for both Japan and the UK. This approach enables rapid broad scale comparisons which can easily identify the more preferential scenarios with finer scale emission sources required after broad approaches have been identified. Therefore, countries have the ability to learn from one another as low carbon energy generation and transport systems are integrated into their respective transport networks. To reduce transport emissions both electrification and decarbonising of the electricity network is required, whilst simultaneously encouraging a shift towards mass transit rather than individual travel. For example, China has encouraged a transition from planes towards ETs, in particular high speed trains as air transportation emits between 100 and 130 gCO_2-e/PKT at full occupancy, implying a significant potential for GHG mitigation (Chang et al., 2019). However, the dominant coal-fired electrical power generation system in China threatens the environmental benefits of rail transportation as this has similar emissions to coal fired steam traction.

Moreover, within this study it is assumed that as number of trains and distance travelled is responsive to population size, the grams of CO_2 per kilometre for Japanese rail had to be estimated as no real data projections were available. Additionally, as ~99% of rail in Japan is electrified the estimation of emissions from DFTs and HTs is hypothetical and were included for comparison purposes. With both countries aiming to decarbonise to meet the Paris Agreement requirements, the outlining of both providing and powering trains to match the public demand will be an important step. Until those policies and targets are set, detailed modelling based on finer scale carbon intensity or market share of ET integration rates is not possible.

Although an economic analysis to determine the feasibility of introducing low carbon rail in Japan and the UK is out with the scope of this paper, the economics of decarbonising transport has been discussed in numerous studies (Nocera and Cavallaro, 2016; Shafiei et al., 2017; Shimada et al., 2007). This shift to low carbon rail has already begun in Japan where most rail lines are electric. Alternatively in the UK, there will be significant investment required to upgrade current technology, however these upgrades are not just driven by goals for carbon emissions, but by economic and safety factors. For example, the operational lifespan of rolling stock is more than 20 years, therefore, new trains entering service in 2020 will still be in service by 2040, long after the net zero target (Logan et al., 2020b). Also, there is the potential for additional associated costs through carbon taxes to dissuade emissions. The costs of investment and policies surrounding ETs and HTs in both countries are unknown. We acknowledge that initial financial implications and GHG emissions of ET and HT infrastructure, including train carriages will be high, but with the anticipated reduction in emissions from hydrogen technology compared to fossil fuel technology these emissions will amortize over time with net overall benefits being substantial within legislative time frames. Energy intensive technologies, like rail has seen a global increased growth of 4% per year, therefore, in numerous countries this remains an economically viable option, although not to the same scale as Japan's low emission rail system (Iyer et al., 2015). Moreover, the power generation sector has a key role in the overall adjustment towards a less carbon intensive economy (Saveyn et al., 2012).

Our results highlight that reducing Japan and the UK's GHG emissions produced from transport cannot simply rely on renewables and energy efficiency. Scientific literature has described other methods to quantify the CO_2 economic costs such as Avoidance Costs (Kuik et al., 2008) or market-based schemes (Nocera and Tonin, 2014), similar to those introduced in the UK. The UK has introduced a carbon cost through renewable obligation certificates, whilst simultaneously incentivising low carbon energy generation through feed-in tariffs (FITs) and Contract for Difference (CfDs) schemes. The money generated from these schemes can then be used to subsidise additional renewable energy construction, replacing fossil fuels, and allowing renewable energy to become more affordable (Fan et al., 2018; Leiren et al., 2020; Logan et al., 2020b). Japan utilises a similar strategy under a domestic carbon pricing policy. For example, in Tokyo producers pay for the carbon costs for the right to emit (Zhou et al., 2013).

Nocera and Tonin (2014) highlighted that the economic estimations associated with transport emissions are important as this has the ability to reduce uncertainty in terms of marginal social costs of carbon. This is due to the relative abundance of CO_2 emission estimates from transport that are available. By reducing uncertainty within models, policymakers are more likely to be able to implement policy that has a successful impact. Nocera and Tonin's (2014) top-down approach allows for the evaluation of carbon emissions to better understand methods to implement transport policy analysis to identify potential risks. This allows for a reduction in uncertainty in carbon emission evaluation by monitoring their effects. Alternatively, a bottom-up approach should allow an estimation of the impacts of the transport system that cause CO_2 emissions by ensuring travel demand, modal share and elasticity can be estimated with some reliability (Libardo and Nocera, 2008). Efficient planning of technical and policy measures could also be implemented to meet transport emission reductions and estimate future investments for new technologies.

However, in many situations, it may be difficult to deal with this uncertainty through probabilistic risk assessments, due to incomplete data sources (Sasidharan et al., 2020; 2017). Therefore, the model used within this paper provides a simplistic approach that considers fewer variables with more assessable results that can be used to compare a broader range of countries for comparison. This model allows for easy substitution of other transport types, directly into the model, since the number of transport types and distances travelled are easy to manipulate man.

In addition, this research highlights the current and expected rail transport use from previous analysis and did not consider the impact that the COVID-19 pandemic could have on the rail network or the emissions produced from the transport sector. Additional analysis will need to consider how to encourage the use of public transport, whilst ensuring individuals feel safe as many will try to reduce their personal risk and opt for personal vehicles (Chiaramonti and Maniatis, 2020). This has the potential to negatively impact the environment as the emissions produced per person per kilometre travelled remain higher for both private internal combustion engine vehicles and electric vehicles than public transport (Logan et al., 2020b; 2020a).

Conclusions

Results from this study indicate that ETs produced lower levels of operating emissions than both HTs and DFTs in both countries. However, both countries will need to take a different approach if they are going to meet the Paris Agreement objectives. As Japan has already electrified a significant proportion of rail lines and trains the focus needs to be on decarbonising the electricity generation mix and transitioning away from fossil fuels. During this transition, the introduction of CCS will allow existing emissions to be minimalised. For the UK, focus has already been placed on decarbonising the energy generation mix with fossil fuels being phased out and emissions decreasing with the introduction of CCS, so the emphasis should be placed on switching towards predominantly electric trains and H_2 for the remainder.

For both countries it is likely that a mix of ETs and HTs may be required to accommodate future travel demand patterns, including operational challenges relating to long distances. Furthermore, promoting increased usage of public transport will need to remain a priority in both countries, with cost and convenience remaining an appealing and enticing factor. Japan's rail network is known for its reliable, punctual and affordable service, however ageing infrastructure will need to be replaced to keep up with demands. On the other hand, if the UK wants to encourage rail uptake over use of personal vehicles, reducing overcrowding will allow a more efficient service as trains are less likely to be delayed, which in turn improves their convenience. With decarbonised energy and a shift towards ETs, both countries could see a significant decrease in rail emissions.

CRediT authorship contribution statement

Kathryn G. Logan: Writing - original draft, Writing - review & editing, Conceptualization, Methodology, Data curation, Formal analysis. **John D. Nelson:** Conceptualization, Resources, Writing - review & editing, Supervision. **Benjamin C. McLellan:** Conceptualization, Data curation, Resources, Writing - review & editing. **Astley Hastings:** Conceptualization, Resources, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

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References

Abe, R., Kato, H., 2017. What led to the establishment of a rail-oriented city? Determinants of urban rail supply in Tokyo, Japan, 1950–2010. Transp. Policy 58, 72–79. https://doi.org/10.1016/j.tranpol.2017.05.004.

Akimoto, K., Takagi, M., Tomoda, T., 2007. Economic evaluation of the geological storage of CO2 considering the scale of economy. Int. J. Greenh. Gas Control 1, 271–279. https://doi.org/10.1016/S1750-5836(06)00003-X.

Alcalde, J., Heinemann, N., Mabon, L., Worden, R.H., de Coninck, H., Robertson, H., Maver, M., Ghanbari, S., Swennenhuis, F., Mann, I., Walker, T., Gomersal, S., Bond, C.E., Allen, M.J., Haszeldine, R.S., James, A., Mackay, E.J., Brownsort, P.A., Faulkner, D.R., Murphy, S., 2019. Acorn: Developing full-chain industrial carbon capture and storage in a resource- and infrastructure-rich hydrocarbon province. J. Clean. Prod. 233, 963–971. https://doi.org/10.1016/J.JCLEPRO.2019.06.087.

Aruga, K., 2020. Analyzing the condition of Japanese electricity cost linkages by fossil fuel sources after the Fukushima disaster. Energy Transitions 4, 91–100. https://doi.org/10.1007/s41825-020-00025-y.

Ashina, S., Fujino, J., Masui, T., Ehara, T., Hibino, G., 2012. A roadmap towards a low-carbon society in Japan using backcasting methodology: Feasible pathways for achieving an 80% reduction in CO2 emissions by 2050. Energy Policy 41, 584–598. https://doi.org/10.1016/J.ENPOL.2011.11.020.

BEIS, 2020. £90 million UK drive to reduce carbon emissions [WWW Document] accessed 5.19.20 https://www.gov.uk/government/news/90-million-uk-drive-to-reduce-carbon-emissions, .

BEIS, 2019a. Digest of UK Energy Statistics (DUKES) 2018 Chapter 5: Electricity [WWW Document] accessed 5.19.20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf, .

BEIS, 2019b. Re-use of oil and gas assets for carbon capture usage and storage projects [WWW Document] accessed 5.19.20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/819901/reuse-oil-gas-assets-ccus-projects.pdf, .

BEIS, 2018a. Implementing the End of Unabated Coal by 2025 [WWW Document] accessed 5.19.20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672137/Government_Response_to_unabated_coal_consultation_and_statement_of_policy.pdf, .

BEIS, 2018b. The Clean Growth Strategy [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf (accessed 5.19.20).

BEIS, 2017. The Clean Growth Strategy: Leading the way to a low carbon future [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf.

Bowman, A., 2015. An illusion of success: The consequences of British rail privatisation. Account. Forum 39, 51–63. https://doi.org/10.1016/J.ACCFOR.2014.10.001.

Bracaglia, V., D'Alfonso, T., Nastasi, A., Sheng, D., Wan, Y., Zhang, A., 2020. High-speed rail networks, capacity investments and social welfare. Transp. Res. Part A Policy Pract. 132, 308–323. https://doi.org/10.1016/j.tra.2019.11.011.

Brand, C., Anable, J., 2019. 'Disruption' and 'continuity' in transport energy systems : the case of the ban on new conventional fossil fuel vehicles, in: Eceee 2019 Summer Study. Giens, near Hyeres, France, pp. 1–12.

Brand, C., Anable, J., Philips, I., Morton, C., 2019. Transport Energy Air pollution Model (TEAM). Methodology Guide (No, UKERC/DM/2019/WP/01).

Brand, C, Anable, J, Ketsopoulou, I, Watson, J, 2020. Road to zero or road to nowhere? Disrupting transport and energy in a zero carbon world. Energy Policy. https://doi.org/10.1016/j.enpol.2020.111334.

Brand, C., Tran, M., Anable, J., 2012. The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. Energy Policy 41, 107–124. https://doi.org/10.1016/J.ENPOL.2010.08.019.

Bugalia, N., Maemura, Y., Ozawa, K., 2019. Demand risk management of private High-Speed Rail operators: A review of experiences in Japan and Taiwan. Transp. Policy. https://doi.org/10.1016/j.tranpol.2019.12.004

Byers, E.A., Hall, J.W., Amezaga, J.M., 2014. Electricity generation and cooling water use: UK pathways to 2050. Glob. Environ. Chang. 25, 16–30. https://doi.org/10.1016/j.gloenvcha.2014.01.005.

CCC, 2018. Reducing UK emissions 2018 Progress Report to Parliament [WWW Document]. https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/ (Accessed 19/12/20).

Chan, S., Miranda-Moreno, L., Patterson, Z., 2013. Analysis of GHG Emissions for City Passenger Trains: Is Electricity an Obvious Option for Montreal Commuter Trains? J. Transp. Technol. 03, 17–29. https://doi.org/10.4236/jtts.2013.32a003.

Chanchetti, L.F., Leiva, D.R., Lopes de Faria, L.I., Ishikawa, T.T., 2020. A scientometric review of research in hydrogen storage materials. Int. J. Hydrogen Energy 45, 5356–5366. https://doi.org/10.1016/j.ijhydene.2019.06.093.

Chang, Y., Lei, S., Teng, J., Zhang, J., Zhang, L., Xu, X., 2019. The energy use and environmental emissions of high-speed rail transportation in China: A bottom-up modeling. Energy 182, 1193–1201. https://doi.org/10.1016/j.energy.2019.06.120.

Chaturvedi, V., Kim, S.H., 2015. Long term energy and emission implications of a global shift to electricity-based public rail transportation system. Energy Policy 81, 176–185. https://doi.org/10.1016/J.ENPOL.2014.11.013.

Chehade, Z., Mansilla, C., Lucchese, P., Hilliard, S., Proost, J., 2019. Review and analysis of demonstration projects on power-to-X pathways in the world. Int. J. Hydrogen Energy 44, 27637–27655. https://doi.org/10.1016/j.ijhydene.2019.08.260.

Chester, M.V., Horvath, A, 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environmental Research Letters. https://doi.org/10.1088/1748-9326/4/2/024008.

Chiaramonti, D., Maniatis, K., 2020. Security of supply, strategic storage and Covid19: Which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport?. Appl. Energy 271,. https://doi.org/10.1016/j.apenergy.2020.115216 115216.

Cooper, S.J.G., Hammond, G.P., 2018. "Decarbonising" UK industry: Towards a cleaner economy. Proc. Inst. Civ. Eng. Energy 171, 147–157. https://doi.org/10.1680/jener.18.00007.

DEFRA, 2019. The draft Clean Air Strategy Summary of responses [WWW Document] accessed 5.19.20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770714/draft-clean-air-strategy-consult-sum-resp.pdf, .

DfT, 2020. Rail Delays and Compensation 2020 [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/927876/rail-delays-and-compensation-report-2020.pdf (accessed 10.25.20).

DfT, 2019. Energy and environment: data tables (ENV) [WWW Document]. ENV0201 Greenh. gas Emiss. by Transp. mode United Kingdom. URL https://www.gov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env (accessed 5.19.20).

EDMC, 2017. Handbook of Japan's & World Energy & Economic Statistics. The Energy Conservation Center, Japan.

ERIA, 2019. Demand and Supply Potential of Hydrogen Energy in East Asia [WWW Document]. URL https://www.g20karuizawa.go.jp/assets/pdf/Demand and Supply Potential of Hydrogen Energy in East Asia.pdf (accessed 5.19.20).

Fan, A., Huang, L., Lin, S., Chen, N., Zhu, L., Wang, X., 2018. Performance Comparison Between Renewable Obligation and Feed-in Tariff with Contract for Difference in UK. In: in: 2018 China International Conference on Electricity Distribution (CICED), pp. 2761–2765. https://doi.org/10.1109/CICED.2018.8592322.

Fernández-Dacosta, C., Shen, L., Schakel, W., Ramirez, A., Kramer, G.J., 2019. Potential and challenges of low-carbon energy options: Comparative assessment of alternative fuels for the transport sector. Appl. Energy 236, 590–606. https://doi.org/10.1016/j.apenergy.2018.11.055.

Fu, P., Pudjianto, D., Zhang, X., Strbac, G., 2019. Evaluating Strategies for Decarbonising the Transport Sector in Great Britain. 2019 IEEE Milan PowerTech., 1–6. https://doi.org/10.1109/PTC.2019.8810865.

Gallardo, F.I., Monforti Ferrario, A., Lamagna, M., Bocci, E., Astiaso Garcia, D., Baeza-Jeria, T.E., 2020. A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.07.050

Gattusoa, D., Restuccia, A., 2014. A tool for railway transport cost evaluation. Procedia - Soc. Behav. Sci. 111, 549–558. https://doi.org/10.1016/j.sbspro.2014.01.088.

Ghaviha, N., Campillo, J., Bohlin, M., Dahlquist, E., 2017. Review of Application of Energy Storage Devices in Railway Transportation. Energy Procedia 105, 4561–4568. https://doi.org/10.1016/j.egypro.2017.03.980.

Global Railway Review, 2018. Britain's railway will see 7,000 new carriages by 2021 [WWW Document] accessed 10.28.20 https://www.globalrailwayreview.com/news/65864/britains-railway-7000-carriages-2021/, .

González-Gil, A., Palacin, R., Batty, P., 2015. Optimal energy management of urban rail systems: Key performance indicators. Energy Convers. Manag. 90, 282–291. https://doi.org/10.1016/j.enconman.2014.11.035.

González-Gil, A., Palacin, R., Batty, P., Powell, J.P., 2014. A systems approach to reduce urban rail energy consumption. Energy Convers. Manag. 80, 509–524. https://doi.org/10.1016/J.ENCONMAN.2014.01.060.

González, R., Hosoda, E.B., 2016. Environmental impact of aircraft emissions and aviation fuel tax in Japan. J. Air Transp. Manag. 57, 234–240. https://doi.org/10.1016/j.jairtraman.2016.08.006.

Hart, D., Howes, J., Madden, B., Boyd, E., 2016. Hydrogen and Fuel Cells: Opportunities for Growth [WWW Document]. E4Tech Elem. Energy. URL https://www.e4tech.com/uploads/files/UKHFC-Roadmap-Final-Main-Report-171116_1_.pdf (accessed 5.19.20).

Haseli, Y., Naterer, G.F., Dincer, I., 2008. Comparative assessment of greenhouse gas mitigation of hydrogen passenger trains. Int. J. Hydrogen Energy 33, 1788–1796. https://doi.org/10.1016/J.IJHYDENE.2008.02.005.

Hayashi, M., Hughes, L., 2013. The policy responses to the Fukushima nuclear accident and their effect on Japanese energy security. Energy Policy 59, 86–101. https://doi.org/10.1016/J.ENPOL.2012.08.059.

Hayashiya, H., 2017. Recent Trend of Regenerative Energy Utilization in Traction Power Supply System in Japan. Urban Rail Transit 3, 183–191. https://doi.org/10.1007/s40864-017-0070-4.

Hensher, D.A., 2007. Sustainable public transport systems: Moving towards a value for money and network-based approach and away from blind commitment. Transp. Policy. https://doi.org/10.1016/j.tranpol.2006.10.004

Hood, C.P., 2006. Shinkansen: From Bullet Train to Symbol of Modern Japan. Social Science Japan Journal. https://doi.org/10.1093/ssjj/jyl020.

IEA, 2017. Railway Handbook 2017: Energy Consumption and CO2 Emissions [WWW Document] accessed 5.19.20 https://uic.org/IMG/pdf/handbook_iea-uic_2017_web3.pdf, .

IEA, 2016. Energy Policies of an IEA Country: Japan 2016 Review [WWW Document] accessed 5.19.20 https://webstore.iea.org/energy-policies-of-iea-countries-japan-2016-review-japanese, .

IEEJ, 2018. IEEJ Outlook 2018 - Prospects and Challanges until 2050 [WWW Document] accessed 5.19.20 https://eneken.ieej.or.jp/data/7748.pdf, .

IGES, 2010. Japan 2050 Low Carbon Navigator: A User's Guide [WWW Document] accessed 5.19.20 http://www.2050-low-carbon-navi.jp/web/files/PDF/usersGuide_e.pdf, .

Ito, K., Morita, Y., Yanagisawa, A., Suehiro, S., Komiyama, R., Shen, Z., 2006. Japan Long-Term Energy Outlook A Projection up to 2030 under Environmental Constraints and Changing Energy Markets [WWW Document]. URL http://eneken.ieej.or.jp/data/en/data/pdf/342.pdf (accessed 5.19.20).

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., Clarke, L., 2015. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technol. Forecast. Soc. Change 90, 103–118. https://doi.org/10.1016/j.techfore.2013.08.025.

Jensterle, M., Narita, J., Piria, R., Samadi, S., Prantner, M., Crone, K., Siegemund, S., Kan, S., Matsumoto, T., Shibata, Y., 2019. The role of clean hydrogen in the future energy systems of Japan and Germany. Berlin adelphi. Last accessed 6, 2019.

Jong, J.C., Chang, E., 2005. Models for Estimating Energy Consumption of Electric Trains. J. East. Asia Soc. Transp. Stud. 6, 278–291. https://doi.org/10.11175/easts.6.278.

Karimi, F., Goulas, A., Barzmehri, M.M., Putri, M.A., 2012. CCS potential in Norway-Exploring the role of flagship projects: The Mongstad and Kårstø case studies. Int. J. Sustain. Water Environ. Syst. 4, 23–34. https://doi.org/10.5383/swes.04.01.003.

Khan, U., Yamamoto, T., Sato, H., 2021. An insight into potential early adopters of hydrogen fuel-cell vehicles in Japan. Int. J. Hydrogen Energy 46, 10589–10607. https://doi.org/10.1016/j.ijhydene.2020.12.173.

Kobayashi, T., 2005. Breakthrough of Japanese Railway 1: Progress of Electric Railways in Japan. Japan Railw. Transp. Rev. 42, 62–69.

Kucharski, J.B., Unesaki, H., 2017. Japan's 2014 Strategic Energy Plan: A Planned Energy System Transition. J. Energy 2017, 1–13. https://doi.org/10.1155/2017/4107614.

Kuik, O., Tol, R.S.J., Brander, L., 2008. Marginal Abatement Costs of Carbon-Dioxide Emissions: A Meta-Analysis. ESRI WP248, June 2008, series-seriesEconomicSocialDublinworkingpapers.

Kurosaki, F., 2018. A study of vertical separation in Japanese passenger railways. Case Stud. Transp. Policy 6, 391–399. https://doi.org/10.1016/j.cstp.2017.09.004.

Kurosaki, F., Alexandersson, G., 2018. Managing unprofitable passenger rail operations in Japan - Lessons from the experience in Sweden. Res. Transp. Econ. 69, 460–469. https://doi.org/10.1016/j.retrec.2018.07.019.

Kurosaki, F., Economics, T., 2017. A Comparative Study of Passenger Through Train Operation Between Japan and Europe. J. East. Asia Soc. Transp. Stud. 12, 316–330. https://doi.org/10.11175/easts.12.316.

Kusakabe, T., Iryo, T., Asakura, Y., 2010. Estimation method for railway passengers' train choice behavior with smart card transaction data. Transportation (Amst). 37, 731–749. https://doi.org/10.1007/s11116-010-9290-0.

Lalive, R., Luechinger, S., Schmutzler, A., 2018. Does expanding regional train service reduce air pollution? J. Environ. Econ. Manage. 92, 744–764. https://doi.org/10.1016/J.JEEM.2017.09.003.

Lam, C.Y., Tai, K., 2020. Network topological approach to modeling accident causations and characteristics: Analysis of railway incidents in Japan. Reliab. Eng. Syst. Saf. 193,. https://doi.org/10.1016/j.ress.2019.106626 106626.

LBST, 2020. 83 new hydrogen refuelling stations worldwide: Presse release [WWW Document] accessed 5.19.20 https://www.h2stations.org/press-release-2020-02-19/, .

Leiren, M.D., Inderberg, T.H.J., Rayner, T., 2020. Policy styles, opportunity structures and proportionality: Comparing renewable electricity policies in the UK. Int. Polit. Sci. Rev. https://doi.org/10.1177/0192512120907112

Lew, D., Piwko, D., Miller, N., Jordan, G., Clark, K., Freeman, L., 2010. How Do High Levels of Wind and Solar Impact the Grid? The Western Wind and Solar Integration Study (No. No. NREL/TP-5500-50057). Golden, CO (United States).

Li, L., 2019. Structure and influencing factors of CO2 emissions from transport sector in three major metropolitan regions of China: estimation and decomposition. Transportation (Amst). 46, 1245–1269. https://doi.org/10.1007/s11116-017-9827-6.

Li, L., Zhang, X., 2020. Reducing CO2 emissions through pricing, planning, and subsidizing rail freight. Transp. Res. Part D Transp. Environ. 87,. https://doi.org/10.1016/j.trd.2020.102483 102483.

Libardo, A., Nocera, S., 2008. Transportation elasticity for the analysis of Italian transportation demand on a regional scale. Traffic Eng. Control 49, 187–192.

Lin, B., Liu, C., Wang, H., Lin, R., 2017. Modeling the railway network design problem: A novel approach to considering carbon emissions reduction. Transp. Res. Part D Transp. Environ. 56, 95–109. https://doi.org/10.1016/j.trd.2017.07.008.

Liu, S., Wan, Y., Ha, H.-K., Yoshida, Y., Zhang, A., 2019. Impact of high-speed rail network development on airport traffic and traffic distribution: Evidence from China and Japan. Transp. Res. Part A Policy Pract. 127, 115–135. https://doi.org/10.1016/j.tra.2019.07.015.

Logan, K.G., Nelson, J.D., Hastings, A., 2020a. Electric and Hydrogen Buses: Shifting from Conventionally Fuelled Cars in the UK. Transp. Res. Part D Transp. Environ. 85. https://doi.org/10.1016/j.trd.2020.102350.

Logan, K.G., Nelson, J.D., McLellan, B.C., Hasting, A., Hastings, A., 2020b. Towards electric and hydrogen Rail: Potential contribution to net zero. Transp. Res. Part D Transp. Environ. 87,. https://doi.org/10.1016/j.trd.2020.102523 102523.

Logan, K.G., Nelson, J.D., Lu, X., Hastings, A., 2020c. UK and China: Will electric vehicle integration meet Paris Agreement Targets?. Transportation Research Interdisciplinary Perspectives 8, 100245. https://doi.org/10.1016/j.trip.2020.100245.

Logan, K.G., Nelson, J.D., Osbeck, C, Chapman, J.D., Hastings, A, 2020d. The application of travel demand management initiatives within a university setting. Case Studies on Transport Policy. https://doi.org/10.1016/j.cstp.2020.10.007.

Macola, I.G., 2020. Explained: the end of the rail franchising system in the UK [WWW Document]. URL https://www.railway-technology.com/features/explained-the-end-of-the-railway-franchising-system-in-the-uk/ (accessed 10.28.20).

Matsuo, Y., Endo, S., Nagatomi, Y., Shibata, Y., Komiyama, R., Fujii, Y., 2018. A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO2-free hydrogen. Energy 165, 1200–1219. https://doi.org/10.1016/j.energy.2018.09.187.

METI, 2017. Basic Hydrogen Strategy [WWW Document] accessed 5.19.20 http://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf, .

Mizutani, J., Fukuda, S., 2020. Issues on modal shift of freight from road to rail in Japan: Review of rail track ownership, investment and access charges after the National Railway restructuring. Res. Transp. Bus. Manag. 100484. https://doi.org/10.1016/j.rtbm.2020.100484.

Görke, R.H., Hu, W., Dunstan, M.T., Dennis, J.s., Scott, S.A., 2018. Exploration of the material property space for chemical looping air separation applied to carbon capture and storage. Applied Energy. https://doi.org/10.1016/j.apenergy.2017.11.083.

Grid, National, 2018. Future Energy Scenarios [WWW Document] accessed 5.19.20 http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf, .

NIC, 2016. High Speed North. https://doi.org/10.1049/el:20061733

Nocera, S., Cavallaro, F., 2016. Economic valuation of Well-To-Wheel CO2 emissions from freight transport along the main transalpine corridors. Transp. Res. Part D Transp. Environ. 47, 222–236. https://doi.org/10.1016/j.trd.2016.06.004.

Nocera, S., Tonin, S., 2014. A Joint Probability Density Function for Reducing the Uncertainty of Marginal Social Cost of Carbon Evaluation in Transport Planning. In: de Sousa, J.F., Rossi, R. (Eds.), Computer-Based Modelling and Optimization in Transportation. Springer International Publishing, Cham, pp. 113–126. https://doi.org/10.1007/978-3-319-04630-3_9.

O'Beirne, P, Battersby, F, Mallett, A, Aczel, M, Makuch, K, Workman, M, Heap, R, 2020. The UK net-zero target: Insights into procedural justice for greenhouse gas removal. Environmental Science and Policy. https://doi.org/10.1016/j.envsci.2020.06.013.

Oliveira, L.C.R., Fox, C., Birrell, S., Cain, R., 2019. Analysing passengers' behaviours when boarding trains to improve rail infrastructure and technology. Robot. Comput. Integr. Manuf. 57, 282–291. https://doi.org/10.1016/j.rcim.2018.12.008.

ONS, 2017. National Population Projections: 2016-based statistical bulletin [WWW Document] accessed 6.6.20 https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2016basedstatisticalbulletin, .

ORR, 2017. Rail infrastructure, assets and environmental 2016–17 Annual Statistical Release [WWW Document] accessed 5.19.20 https://dataportal.orr.gov.uk/media/1520/rail-infrastructure-assets-environmental-2016-17.pdf, .

Oura, Y., Mochinaga, Y., Nagasawa, H., 1998. Railway Technology Today 3 (Edited by Kanji Wako) Railway Electric Power Feeding Systems. Japan Railw. Transp. Rev. 8, 81–83.

Pale Blue Dot, 2017. Mighty CCS projects from little Acorns grow [WWW Document]. Mighty CCS Proj. from little Acorns grow. URL https://pale-blu.com/2017/05/10/mighty-ccs-projects-from-little-acorns-grow/ (accessed 10.28.19).

Power, C., Mian, J., Spink, T., Abbott, S., Edwards, M., 2016. Development of an Evidence-based Geotechnical Asset Management Policy for Network Rail. Great Britain. Procedia Eng. 143, 726–733. https://doi.org/10.1016/j.proeng.2016.06.112.

Pridmore, A., 2009. Carbon footprinting of policies, programmes and projects [WWW Document]. URL http://www.pteg.net/system/files/general-docs/AEAPTEGCarbonFootprintingfinalversion2009.pdf (accessed 5.19.20).

Priestley, S., 2019. UK Carbon Budgets [WWW Document]. House Commons Libr. URL https://commonslibrary.parliament.uk/research-briefings/cbp-7555/ (accessed 5.19.20).

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °c. Nature 534, 631–639. https://doi.org/10.1038/nature18307.

Royston, S.J., Gladwin, D.T., Stone, D.A., Ollerenshaw, R., Clark, P., 2019. Development and Validation of a Battery Model for Battery Electric Multiple Unit Trains. IECON 2019–45th Annu. Conf. IEEE Ind. Electron. Soc. 1, 4563–4568. https://doi.org/10.1109/iecon.2019.8927299.

Sasidharan, M., Burrow, M.P.N., Ghataora, G.S., 2020. A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance. Res. Transp. Econ. 80,. https://doi.org/10.1016/j.retrec.2020.100815 100815.

Sasidharan, M., Burrow, M.P.N., Ghataora, G.S., Torbaghan, M.E., 2017. A Review of Risk Management Applications For Railways. Railw. Eng. 3100.

Progressive Energy Ltd, 2019. HyMotion Network-supplied hydrogen unlocks low carbon transport opportunities [WW DOC] https://hynet.co.uk/app/uploads/2019/06/15480_CADENT_HYMOTION_PROJECT_REP.pdf (Accessed 21/03/2021).

Sato, K., Koinuma, K., Tomii, N., 2018. A train rescheduling algorithm which minimizes passengers' dissatisfaction based on MILP formulation, in: CASPT2018-Conference on Advanced Systems in Public Transport and TransitData 2018.

Saveyn, B., Paroussos, L., Ciscar, J.-C., 2012. Economic analysis of a low carbon path to 2050: A case for China. India and Japan. Energy Econ. 34, S451–S458. https://doi.org/10.1016/j.eneco.2012.04.010.

The Scottish Government, 2017. Nuclear energy. [WWW DOC] https://www.gov.scot/policies/nuclear-energy/ (Accessed 21/03/2021)..

Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., Stolten, D., 2015. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. Int. J. Hydrogen Energy 40, 4285–4294. https://doi.org/10.1016/j.ijhydene.2015.01.123.

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., Asgeirsson, E.I., 2017. Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity. J. Clean. Prod. 141, 237–247. https://doi.org/10.1016/J.JCLEPRO.2016.09.064.

Shimada, K., Tanaka, Y., Gomi, K., Matsuoka, Y., 2007. Developing a long-term local society design methodology towards a low-carbon economy: An application to Shiga Prefecture in Japan. Energy Policy 35, 4688–4703. https://doi.org/10.1016/j.enpol.2007.03.025.

Shiraki, H., Matsumoto, K., Shigetomi, Y., Ehara, T., Ochi, Y., Ogawa, Y., 2020. Factors affecting CO2 emissions from private automobiles in Japan: The impact of vehicle occupancy. Appl. Energy 259,. https://doi.org/10.1016/j.apenergy.2019.114196 114196.

Sims, R.E.H., Hastings, A., Schlamadinger, B., Taylor, G., Smith, P., 2006. Energy crops: Current status and future prospects. Glob. Chang. Biol. 12, 2054–2076. https://doi.org/10.1111/j.1365-2486.2006.01163.x.

Smithers, A., 2020. National Rail Route Diagram [WWW Document]. http://www.projectmapping.co.uk/Resources/Rail map v30c curvy.pdf (Accessed 13/02/.21).

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N., Ward, K.R., 2019. The role of hydrogen and fuel cells in the global energy system. Energy Environ. Sci. 12, 463–491. https://doi.org/10.1039/c8ee01157e.

Statistica, 2020. Distribution of the payload distance in domestic passenger transportation in Japan in fiscal year 2017, by mode of transport [WWW Document]. URL https://www.statista.com/statistics/626747/japan-domestic-passenger-transport-volume-share-by-mode/?fbclid=IwAR2y981oXo5U7oRJkqXvFS9_OxijA8tMZh 05Ykne7RmCjISNwhY65R0UM50 (accessed 5.27.20).

Steinberg, B.A., Scott, D.S., 1984. Hydrogen vs diesel fueled locomotives: a technoeconomic appraisal. Int. J. Hydrogen Energy. https://doi.org/10.1016/0360-3199(84)90037-5

Sugiyama, M., Fujimori, S., Wada, K., Endo, S., Fujii, Y., Komiyama, R., Kato, E., Kurosawa, A., Matsuo, Y., Oshiro, K., Sano, F., Shiraki, H., 2019. Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges. Energy 167, 1120–1131. https://doi.org/10.1016/j.energy.2018.10.091.

Tanaka, Y., Abe, M., Sawada, Y., Tanase, D., Ito, T., Kasukawa, T., 2014. Tomakomai CCS Demonstration Project in Japan, 2014 Update. Energy Pro 63, 6111–6119. https://doi.org/10.1016/j.egypro.2014.11.643.

The World Bank, 2018. Electric power transmission and distribution losses (% of output) [WWW Document] accessed 6.3.20 https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS, .

Thomas, J.M., Edwards, P.P., Dobson, P.J., Owen, G.P., 2020. Decarbonising energy: The developing international activity in hydrogen technologies and fuel cells. J. Energy Chem. 51, 405–415. https://doi.org/10.1016/j.jechem.2020.03.087.

Trencher, G., Taeihagh, A., Yarime, M., 2020. Overcoming barriers to developing and diffusing fuel-cell vehicles: Governance strategies and experiences in Japan. Energy Policy 142,. https://doi.org/10.1016/j.enpol.2020.111533 111533.

UNFCCC, 2008. Kyoto Protocol Reference Manual [WWW Document]. United Nations Framew. Conv. Clim. Chang. https://doi.org/10.5213/jkcs.1998.2.2.62

Vivoda, V., 2012. Japan's energy security predicament post-Fukushima. Energy Policy 46, 135–143. https://doi.org/10.1016/J.ENPOL.2012.03.044.

Wang, T., Qu, Z., Yang, Z., 2020. How does the UK transport system respond to the risks posed by climate change? An analysis from the perspective of adaptation planning. Marit. Transp. Reg. Sustain. 85–106. https://doi.org/10.1016/B978-0-12-819134-7.00006-X.

Watabe, A., Leaver, J., Ishida, H., Shafiei, E., 2019. Impact of low emissions vehicles on reducing greenhouse gas emissions in Japan. Energy Policy 130, 227–242. https://doi.org/10.1016/j.enpol.2019.03.057.

Williams Rail Review, 2019. The role of the railway in Great Britain [WWW Document] accessed 5.19.20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/782063/role-of-railway-evidence-paper-rail-review.pdf, .

Yamamoto, H., 1993. Transportation in the Postwar Recovery Period (1946-1954): Policy, in: Technological Innovation and the Development of Transportation in Japan. United Nations University Press.

Zenith, F., Isaac, R., Hoffrichter, A., Thomassen, M.S., Møller-Holst, S., 2019. Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries: Case studies in Norway and USA. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit. https://doi.org/10.1177/0954409719867495

Zhou, X., Yano, T., Kojima, S., 2013. Proposal for a national inventory adjustment for trade in the presence of border carbon adjustment: Assessing carbon tax policy in Japan. Energy Policy 63, 1098–1110. https://doi.org/10.1016/j.enpol.2013.09.016.