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Getting It Right on the Policy Prioritization for Rail Decarbonization: Evidence From Whole-Life CO_{2e} Emissions of Railway Systems

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INTRODUCTION

In the past several years, global warming has caused essential issues that all sectors must respond immediately. The Paris Agreement has turned into a critical framework provoking public and private sectors worldwide (Dimitrov, 2016; Pye et al., 2017). One approach to solving this problem involves the use of green energies and reducing CO₂ emitted from all sectors.

Regarding the transportation sectors, it emitted CO₂ above one-fourth of the global emission. A well-known problem with over emission is that some countries have inadequate public transportation and non-environmental policies. The low-fare service and high accessibility on public transit are major strategies to reduce emission from a private car (Krishnan et al., 2015; De Andrade and D'Agosto, 2016). These schemes eventually promote a long-term shift from self-vehicle to public transportation services. The United Kingdom government has been concerned with the global warming issue and provided new strategies to reduce CO₂ emission in all sectors, such as launching new public transportation (Kaewunruen et al., 2018; Logan et al., 2020). Additionally, the United Kingdom's railway network is considered the lowest CO₂ emission per passenger over other public services. Regarding the global climate policies, the United Kingdom government has still intended to cut off the railway's emission by replacing it with alternative fuels and changing the current diesel engine system toward the decarbonization concept, mainly reducing the emission from the operational process.

Even though the CO₂ emission from the railway's life cycle predominantly comes from the railway infrastructure, the United Kingdom government and rail sectors exceptionally focus on reducing those emissions from the operational stage. In this research, the authors believe that only promoting strategies to reduce CO₂ in the operational process cannot bring the United Kingdom government to reach its targets by 2050. In contrast, the government should also consider other effective and practical strategies.

In order to understand the amount of CO₂ emission from the railway network, the research deeply examines the entire life cycle analysis (LCA) through the high-speed rail (HSR)'s infrastructure. This research aims to provide future strategies and policies to cut the CO₂ off the railway network. Furthermore, the decarbonization concepts and practical approaches to the railway system have been stated in this study.

THE DECARBONIZATION CONCEPT IN THE RAILWAY SYSTEM

The Paris Agreement has been launched as a global environmental policy. It targets to keep global temperature below 1.5°C compared with the pre-industrial era (Dimitrov, 2016; Streck et al., 2016). The agreement has been involved in the transportation industry, especially on railway and HSR networks. Implementing environmental concepts becomes a challenging issue for researchers and engineers in the railway industry. The International Union of Railways (UIC)'s report states that transportation shared 24.7% of CO₂ emission or 8 billion tCO₂. The railway sector, well-known as the lowest CO₂ emitter, has produced 26.64 million tCO₂ across the European countries (Korea Ministry of Land, 2008; Kaewunruen et al., 2016; UIC, 2017). Also, many attempts to reduce global emission have been applied to the railway industry. There were several collaborations among railway industries, operators, policymakers, and other related sections to respond to governmental policies.

Based on the United Kingdom's targets to achieve net-zero by 2050 and reduce 80% of greenhouse gases (GHGs) emissions relative to 1990 levels (GOVUK, 2019; ORR, 2019). The principal of the net-zero refers to the balance between the emitted GHGs and their amount in the atmosphere. The discharged and taken out GHGs can be equivalent by using high technologies such as carbon capture and carbon storage (Bonsu, 2020). In fact, the GHGs are mainly composed of CO₂; hence, the amount of emission is commonly measured in the CO₂ unit. Moreover, the government launches the net-zero plan to produce low carbon industries across the United Kingdom. Nevertheless, the strategies are unable to bring the United Kingdom to reach its targets due to a lack of reducing CO₂ emissions in other sections such as infrastructural emission.

Department for Transport (DfT)'s report (2020) reveals that the decarbonization plan decreases 43% of emissions while increasing the country's economy by 75%. It illustrates significantly advanced progress over other sectors. The Rail Safety and Standards Board (RSSB) states that the United Kingdom's rail system has a high potential to provide net-zero carbon by 2050 (ORR, 2019; LSE, 2020). The statement confirms the United Kingdom's rail network in response to European's policy toward a decarbonizing framework. Following the global guidelines, the United Kingdom's government has proposed a vision to remove all diesel trains from the network by 2040. According to the United Kingdom railway network, it has been widely linked across the country in a total of 16,209 km of distance (Stittle, 2004; Network Rail, 2020). The railway takes 2% market share of public transportation and 10% of passenger mile traveled in Great Britain. The transport sector's emission shows at 28%, which the rail sector shared 3% of total transport's emission (Power et al., 2016; ORR, 2019; RSSB, 2019). The rail network is expected to use electrical and other renewable sources as alternative energy. Moreover, an effective plan to reduce CO₂ from the network is adopted in all related rail activities, that is, using zero-carbon self-powered vehicles, increasing energy efficiency, and reducing pollution emissions.

The decarbonization concept refers to the termination of CO₂ emission from fossil fuel (RSSB, 2019). The government plans to operate an entire network without CO₂ emission by 2050. All diesel trains will not be allowed in the United Kingdom's rail network, and the existing engines need to be replaced with an electric system. Moreover, the government is encountering unsupported infrastructural issue because only 42% of the United Kingdom's network is an electrical track (RSSB, 2019). Alternative energies have been applied to the railway network, such as hydrogen (H₂) fuel cell, battery, solar energy, and biomass. Some research compares an engine performance between the existing diesel trains and electric trains. The outcomes state that the fuel cell and the electrification systems do not significantly improve the train's performance. In contrast, the H₂ train has higher efficiency than other low-carbon vehicles, but it is the most expensive option (Anandarajah et al., 2013). The electric hybrid vehicle is highly recommended as it is able to reduce the fuel consumption by more than 20%. As a result, the GHG emission can be reduced up to 15–30% (Cheli et al., 2006).

In this day, the United Kingdom's HSR network, namely, "HS2," has been continually constructed. The HS2 project strictly follows the government's net-zero targets and decarbonization concept since the beginning of the construction phase (HS2, 2021). The HSR service has limited the lower speed at 250 km/h, while the conventional rail's speed at 200 km/h. The HS2 project is expected to be the most sustainable railway network in the world, reducing CO₂ emission than cars and planes. Regarding the future developments toward the rail network, the decarbonization vision should be turned into practice. The government must consider the cost of electrical track and power engines replacement.

THE LIFE CYCLE ANALYSIS OF HIGH-SPEED RAIL'S INFRASTRUCTURE

The LCA, a tool to identify environmental impacts along the life cycle, is applied to this research. This assessment clearly shows the CO₂ emission in each life cycle stage that leads to sustainable development. To overcome this problem, some approaches have also been made with the decarbonization of the railway. The outcomes have precisely estimated the CO₂ emission from each LCA stage; moreover, the insight provides practical recommendations to reduce the railway system's emission.

The LCA of HSR's infrastructure consists of manufacturing, operation, maintenance, and demolition (Kaewunruen et al., 2019). The manufacturing stage comprises rail track construction that the CO₂ is emitted during its construction and logistic processes. The three characteristics of the rail infrastructure include ballasted track, bridge, and tunnel. The material requirements on each characteristic are dissimilar, caused by the unequal amount of their emissions, as shown in **Table 1**.

The research compares ballasted track, tunnel, and bridge in terms of embodied energy requirement and CO₂ emission. The results clearly show that the ballasted track, which consumes 1,712,694 kJ and emits 4,727 kg CO₂, is the lowest emitter. The

TABLE 1 | The summary of material used (μ : kg), embodied energy (ω : kJ/kg), and emission (ρ : kgCO₂/km) in 1st km of ballasted track, tunnel, and bridge (adopted from the Department for Business, Energy and Industry Strategies, 2020; Global source, 2020).

Material(s)	Ω	ρ	Ballasted track			Tunnel			Bridge		
			μ	ω	ρ	μ	ω	ρ	μ	Ω	ρ
Gravel/Sand	1,000	4.32	530	530,000	2,290	696	696,000	3,007	0	0	0
Concrete	9,500	0.13	34.3	325,850	4	465	4,417,500	60	673	6,393,500	87
Steel	235,200	1350	1.3	305,760	1,755	14.7	3,457,440	19,845	36.8	8,655,360	49,680
Steel low-allowed	244,000	1.77	0.74	180,560	1	1.58	385,520	3	0	0	0
Zinc	490,000	3.41	0	0	0	0.006	2,940	<1	0	0	0
Copper wire	882,200	1612	0.42	370,524	677	0.055	48,521	89	0	0	0
Ceramics	33,330	2.537	0	0	0	1.6	53,328	4	0	0	0
Aluminum alloy	211,850	9110	0	0	0	0.05	10,593	456	0	0	0
PVC	158,000	0.48	0	0	0	0.0653	10,317	<1	0	0	0
Excavation soil	800	0.0048	0	0	0	4,850	3,880,000	23	0	0	0
Summary			–	1,712,694	4,727	–	12,962,159	23,487	–	15,048,860	49,767

CO₂ emission from the ballasted track is lower than that in rail's tunnel and bridge five and ten times, respectively.

The maintenance and operational stages are necessary to maintain the safety conditions of rail infrastructure. The operational and maintenance stages are typically the longest phase in the lifecycle. Moreover, these stages include the standard operation plan, emergency operation, and related activities (Kaewunruen et al., 2019; Li and Zhang, 2020). This research examines LCA with an assumption of significant operation and maintenance that are allocated every 5 years. And, the material requirements are estimated at 15% on the amount of initial construction. The timeframe of infrastructure's LCA is placed at 70 years. As a result, the total emission of these stages is 9,927.56 kgCO₂/km.

Last, the demolition stage is assigned at the final step and aimed at recycling non-using parts. All of the nonrecyclable materials with the toxic chemical are cleaned up. Then, they are transferred to the shredding process and landfill. On the other hand, recyclable parts such as steel, concrete are sent to cleaning, crushing and shredding processes. The small pieces of materials are shifted to the melting process for reforming to the new products. The rail infrastructure composed the recyclable and nonrecyclable parts. In this study, the ballasted track, which is the majority, is analyzed toward the demolition stage (Network Rail, 2020; Rungskunroch et al., 2021). As a result, the calculation shows that the final stage emits 0.248 kgCO₂/km.

In conclusion, the LCA's result reveals 14,655.22 kgCO₂/km. The fractions of emission in manufacturing, operation and maintenance, and demolition are shared at 32.25, 6, and 0.001%, respectively. It can conclude that a significant amount of CO₂ emission comes from operation and maintenance.

DISCUSSIONS AND RECOMMENDATIONS

Following the national energy consumption statistics, the total GHG emission is 351.1 million tonnes (Mt), containing 280.88 MtCO₂ (Department for Business, Energy and Industrial Strategy, 2020). The transportation sector denotes 28% of total emission across the United Kingdom, whereas the

railway network shares only 2% of CO₂ emission of that sector (RSSB, 2019). It can be estimated that CO₂ emission from the United Kingdom rail network is 15.72 MtCO₂ or 970.40 tCO₂/km per annual. The Office of Rail and Road (ORR) reports that the United Kingdom's CO₂ emission for passenger train shows at 36.6 gCO₂ per passenger kilometer (pkm), whereas 25.3 gCO₂ per tonne-kilometer (tkm) from freight train emission (ORR, 2019).

Since eliminating diesel train is not enough response to the government's targets, the implications of these findings are discussed as the solutions to tackle the CO₂ emission from the United Kingdom railway network as follows:

Railway Infrastructure Construction and Maintenance

Various policies have been announced without concerns for the improvement of railway structure. The LCA's infrastructure results show that 14,655.22 kgCO₂/km is emitted in the 70 years of timeframe. It can also be increased to 72,811.52 and 154,284.07 kgCO₂/km on constructing a rail's tunnel and bridge, respectively. Most of the CO₂ emission occurs at the operational and maintenance stages. Moreover, the volume of emissions can be increased when the track requires remarkable maintenance, that is, severe accident, natural disaster, and vandalism. Hence, the emissions by infrastructural activities should not be neglected. Future research should consider the negative effects of CO₂ during infrastructural construction and maintenance carefully (Kaewunruen et al., 2014; Kaewunruen et al., 2015, Kaewunruen et al., 2016).

Replacement of Diesel Engine

RSSB reports that 80% of the traveling distance uses electric trains, and the rest diesel trains. The United Kingdom government has faced political issues of buying the new freight train because none of the current models meets the United Kingdom's net zero-emission targets (Stittle, 2004; Kaewunruen and Lee, 2017). Therefore, the existing freight trains, which are high-level of CO₂ emission, must be continually serviced. This research highly recommends replacing diesel engines with an H₂ fuel cell or biofuel. These alternative sources offer lower CO₂ emission and reduce energy consumption than the diesel model.

Installation of Electric Track Along With the United Kingdom Rail Network

42% of the entire network is an electric track. It means that only those numbers of tracks can push the government's targets forward. Some researchers offer critical development on the environmental perspectives by installing electric tracks (Marin et al., 2010; Kirkwood et al., 2016; Krezo et al., 2018; Chovančíková and Dvořák, 2019). This study also recommends replacing the standard track with the electric track for long-term sustainability goals. Future research on electric track might provide cost details and efficiency about direct current (DC) and alternate current (AC) networks. As found, the DC network shows tangible benefits in terms of power control and noise nuisance (Alnuman, Gladwin and Foster, 2018), while the AC network offers low heat loss.

CONCLUSION

Regarding the Paris Agreement, the United Kingdom government responds to that by planning to make zero-emission across the United Kingdom by 2050. Leading strategies push forward governmental regulation by removing diesel trains out of the network by 2040. Nevertheless, the emission of CO₂ in the railway network occurs from various sections. Therefore, the LCA is applied to rail infrastructure to precisely describe the CO₂ emission on each lifecycle stage. As shown, the CO₂ predominantly emits from operation and maintenance stages. In this study, both LCA stages have emitted approximately 60% of the total emission in a whole life cycle. It brings the total emission of infrastructure at least 14,655.22 kg CO₂/km.

Conversely, the CO₂ emission in the railway operational stage is 36.6°g CO₂/pkm annually, which exceedingly depends on the volume of a passenger. The research's broad implication

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- Department for Business, Energy and Industrial Strategy (2020). 2019 UK Greenhouse Gas Emission, Provisional Figure. Available at: [is that the railway system's reduction of CO₂ emission should be widely considered along with the rail network, especially on the railway infrastructure. Our study provides three realistic key developments covering infrastructure, electric rail track, and vehicle's engine power. By following these guidelines, the United Kingdom government's target to be net-zero carbon is more achievable.](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_</p>
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AUTHOR CONTRIBUTIONS

PR carried out data analytics and visualization. PR and SK developed the concept and methodology for the investigation. All authors contributed in the writing of the opinion paper.

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