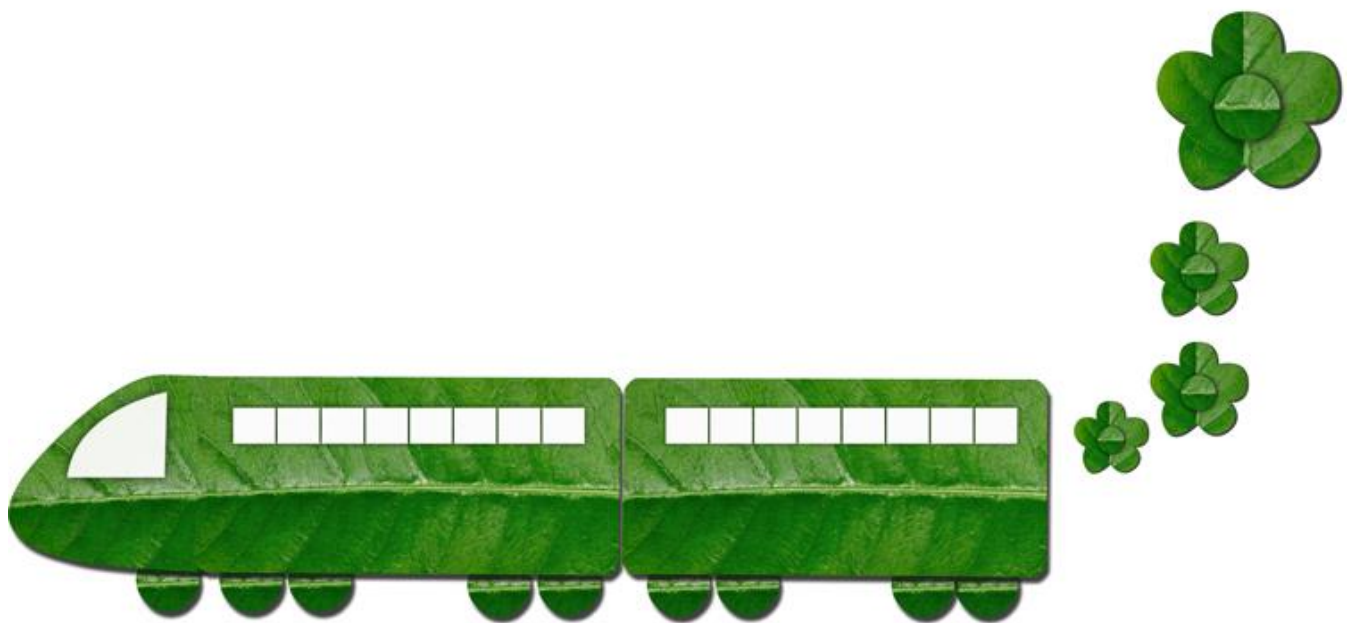


Enhancing shift towards Sustainable Freight Transport in Asia and the Pacific-

Opportunities through railway decarbonization



This study was prepared by Mr. Alexander Burrows, Mr. Stuart Hillmansen and Mr. Marcelo Blumenfeld from the Birmingham Centre for Railway Research and Education, under the supervision of Mr. Sandeep Raj Jain, Transport Connectivity and Logistics Section (TCLS), Transport Division, ESCAP. Overall guidance was provided by Ms. Azhar Jaimurzina Ducrest, Chief, TCLS, Transport Division.

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Key Messages

1. The transport sector is responsible for around one third of global energy consumption and about a quarter of global greenhouse gas emissions. Left unchecked the environmental burden from the transport sector could increase substantially by 2050. Decarbonizing transport has become one of the main strategic responses to reduce carbon emissions that cause climate change.
2. There are two ways rail can contribute to decarbonize the transport, first by modal shift, as railways can carry approximately 40 times more passengers per square metre and consume only a third of fuel to carry a tonne-km of freight as compared to road transport thereby reducing overall emissions.
3. The second way, that is subject of this report, is to decarbonize the rail itself making it a practically zero emission transport mode.
4. Currently only one third of rail network in the ESCAP region is electrified -indicating substantial use of diesel for traction and non-traction purposes. And the diesel-powered trains emit at least twice as much CO₂ in the atmosphere than electric ones.
5. Railway decarbonize solutions entail (a) electrification of rail infrastructure (b) rolling stock that runs on alternative modes of traction such as hydrogen fuel cells, batteries and biodiesel.
6. The findings in the study highlight that some countries in the ESCAP region may not be able to afford or economically justify high investments required in electrification of rail infrastructure. Moreover, impact of rail electrification on carbon emissions is closely linked to energy source to generate electricity. Only use of renewable sources of energy can reduce emissions through rail electrification.
7. Electric battery and hybrid hydrogen fuel cell traction systems are gaining prominence as alternatives to the more costly traditional decarbonisation methods. There are still

barriers and challenges to the implementation of these alternatives that may not be entirely addressed by market forces and may need policy interventions.

8. The railway in ESCAP countries operate distinct traffic volumes over various levels of infrastructure highlighting the challenges of addressing the region with a single solution to decarbonize.
9. The study recommends clustering of countries according to a set of acceptable geo-political, economic, and operational criteria to develop decarbonization pathways that identify specific solutions and appropriate supporting policies to transform low-carbon railway freight into a reality.
10. For specific railway, the study provides a maturity assessment matrix as a strategic tool for railways to map their maturity levels and capabilities for railway decarbonization along the four parameters, namely, sources of electric supply, supporting infrastructure, financing availability and management priorities.

Executive summary

Decarbonisation has become one of the main topics within strategy and decision making across the globe due to heightened concerns on climate change. Forecasts highlight the urgency for drastic actions needed to avoid irreversible environmental damage and climate change, which include the change in the way that people and goods are moved within and between borders. There is extensive body of research that positively correlates the quality and robustness of transport infrastructure with economic growth and societal benefits.

On the other hand, the transport sector has been a prominent contributor to the climate emergency that requires urgent action, especially regarding the reduction of the carbon intensity of the sector, to prevent irreversible environmental damages at a global level. The main aim of this report is to explore not only the role of the railways in the efforts to decarbonise the transport sector, but also to investigate low-cost solutions to decarbonise rail transport in Asia and the Pacific.

To do so, this report includes a literature review of the current state of the freight railway sector in the region, together with a case study of the development of dedicated freight corridors in India and their impact on their national efforts to reduce greenhouse gas (GHG) emissions.

Building on the successful case study of the Indian Railways in railway electrification of new and existing routes, our main findings also highlights that some countries in the Asia and the Pacific region may not be able to afford or economically justify the high investments in that type of infrastructure. ESCAP countries operate distinct traffic volumes over various levels of infrastructure, which highlights the challenges of addressing the region with a single solution.

In light of recent technological developments, battery electric and hybrid hydrogen fuel cell traction systems have gained prominence as alternatives to the more costly traditional decarbonisation methods. The former, as the name suggests, uses large battery units, usually consisting of thousands of cells, to produce equivalent horsepower to diesel locomotives. The latter, which generates electricity from the chemical energy of hydrogen and oxygen, stands as one of the cleanest solutions available.

There are still a few barriers and challenges to the implementation of these alternatives that may not be entirely addressed by market forces. Batteries are made of non-renewable components and have end-of-life issues with disposal, and hydrogen fuel cell systems must be accompanied with the capability to produce and transport the fuel.

All in all, we identify that not only electrification but also new technologies have established a strong landscape that enables the decarbonisation of railway freight operations in Asia and

the Pacific. The continent enjoys abundant supply of energy sources that are crucial to the viability of the transition. Should countries be clustered according to a set of geo-political, economic, and operational criteria, roadmaps can identify specific solutions and appropriate supporting policies to transform low-carbon railway freight into a reality.

This report therefore aims to provide strategic advice for decarbonisation of freight railway services taking into consideration the particular developments in each country of the UNESCAP region. In order to do this, it has the following objectives:

- Analyse railways in the region to establish the context for decarbonised traction systems
- Analyse available decarbonised traction systems to establish their suitability
- Provide a maturity matrix as a strategic tool for policy makers
- Provide recommendations and relevant advice for countries looking to decarbonise their railways

1. Background

The window for safeguarding the planet from extreme consequences of the environmental impacts of human activities is becoming smaller as we move further into the 21st century. It has been over 30 years since the seminal work of the UN World Commission on Environment and Development, *Our Common Future*, set the precedents to rationalising the use of natural resources to protect the economic and social development of future generations¹. According to estimates, human activities have already caused approximately 1.0°C of global warming above pre-industrial levels, and is likely to reach 1.5°C between 2030 and 2052 at the current rate². This means that, should all remain unchanged, extreme weather events will become more frequent which, added by rising sea levels, can lead to serious disruption to ecosystems and the built environment.

These concerns, while drastic in their predictions, are supported by extensive evidence. A review by Ritchie and Hoser (2018) has found that global energy consumption grew almost eight-fold in the last 100 years³. More specifically, the almost exponential growth in energy consumption began in the post-war period when other fossil fuels such as oil and gas were added to the mix. The link between economic growth and environmental impacts is widely known and, considering that passenger transport volumes have risen eleven-fold in the same period⁴, one could infer that transport has shared a significant part in that increase. In fact, the transport sector is responsible for approximately 60 per cent of all oil consumption in OECD countries⁵

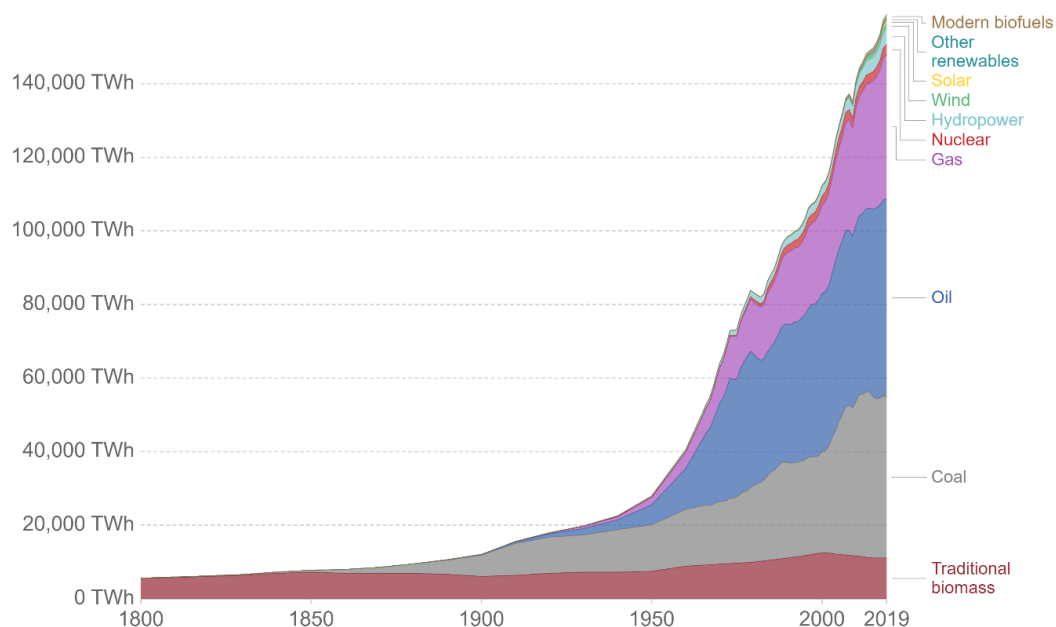


Figure 1. Global energy consumption by fuel (Ritchie and Hoser, 2018)

The transport sector is responsible for 36 per cent of the total energy consumed globally, and road transport alone is responsible for approximately 60 per cent of that amount⁶. Left unchecked and added to the increasing motorisations levels in the developing world, the environmental burden from the transport sector could increase substantially, comprising an increase in up to 82 per cent in energy consumption and 79 per cent in CO₂ emissions by 2050⁷. Of this growth, much is expected to come from the accelerated economic development of low and middle-income countries in Africa and Asia.

Such need for urgent action has prompted governments and industry alike to increase the efforts to reduce the externalities of the transport sector. In a sector that has been dominated by road transport for decades, addressing the Sustainable Development Goals (SDGs) requires significant change. However, the challenge transcends political will as it will also require a considerable commitment to investments, especially in low and lower middle-income countries (LMICs). Rozenberg and Fay (2019) have found that, with the right policies, these countries may need to invest up to 8 per cent of their GDPs to achieve the infrastructure-related Sustainable Development Goals (SDGs) and stay on track to limit climate change to 2°C⁸.

That is where we find ourselves in the crossroads for sustainable transport futures, because more sustainable modes such as railways are usually linked to greater investment requirements, both in capital and operational expenditures.

On the one hand, railways are intrinsically linked to the Sustainable Development Goals (SDGs), in that they are much more efficient than road transport. Railways can carry 40 times more passengers per square metre, and consume only a third of fuel to carry a tonne-km⁹. Railways also impose much lower externalities than road transport. Figure 2 highlights the differences of rail transport compared to their road and air counterparts. For instance, the African Development Bank has found that railways can offer a reduction of up to 87 per cent in the external costs compared to road per thousand tonne-km, and over 81 per cent per passenger-km, especially in relation to air pollution, climate change, and accidents¹⁰.

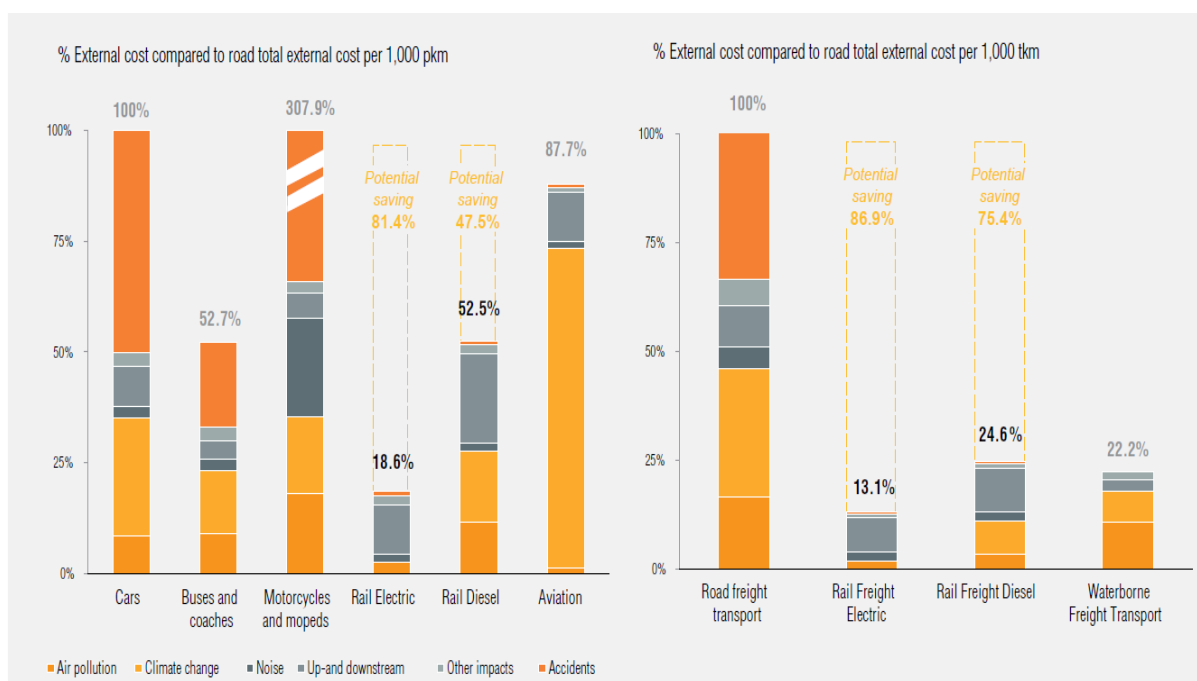


Figure 2. External costs of railways compared to other modes of transport¹⁰

These numbers show the enormous benefits that the increase in rail transport use can bring, when considering the proportion of global traffic volumes found in ESCAP region. According to the International Union for Railways (UIC), the continent carries 75 per cent of the passenger-km and 38 per cent of the tonne-km through a network that accounts for 33 per cent of the total km in the world⁹. This means, considering ESCAP country members, a total of 7.2 trillion tonne-km and 3.4 trillion passenger-km annually^{11,12}. The extent of savings in emissions is considerable. As a rough estimate, should these movements be done by road-based modes, it would mean an additional 2.2 million tonnes of CO₂ annually in the atmosphere.

One can then imagine the reduction in externalities if railway accounted for a greater share of the transport mix in Asia and the Pacific. For instance, if 10 per cent of the 84 billion tonne-km shipped by air in ESCAP member countries was done by train, it would result in saving approximately 13 million tonnes of CO₂ from being released annually in the atmosphere^{13,14}.

In addition, every tonne-km transferred from road vehicles to electrically powered rail could save 100 g of CO₂ per annum. Figure 3 illustrates the significant savings in emissions that moving people and goods by rail could promote. This is particularly applicable to Asia and the Pacific where distances covered can be as long as long-haul flights.

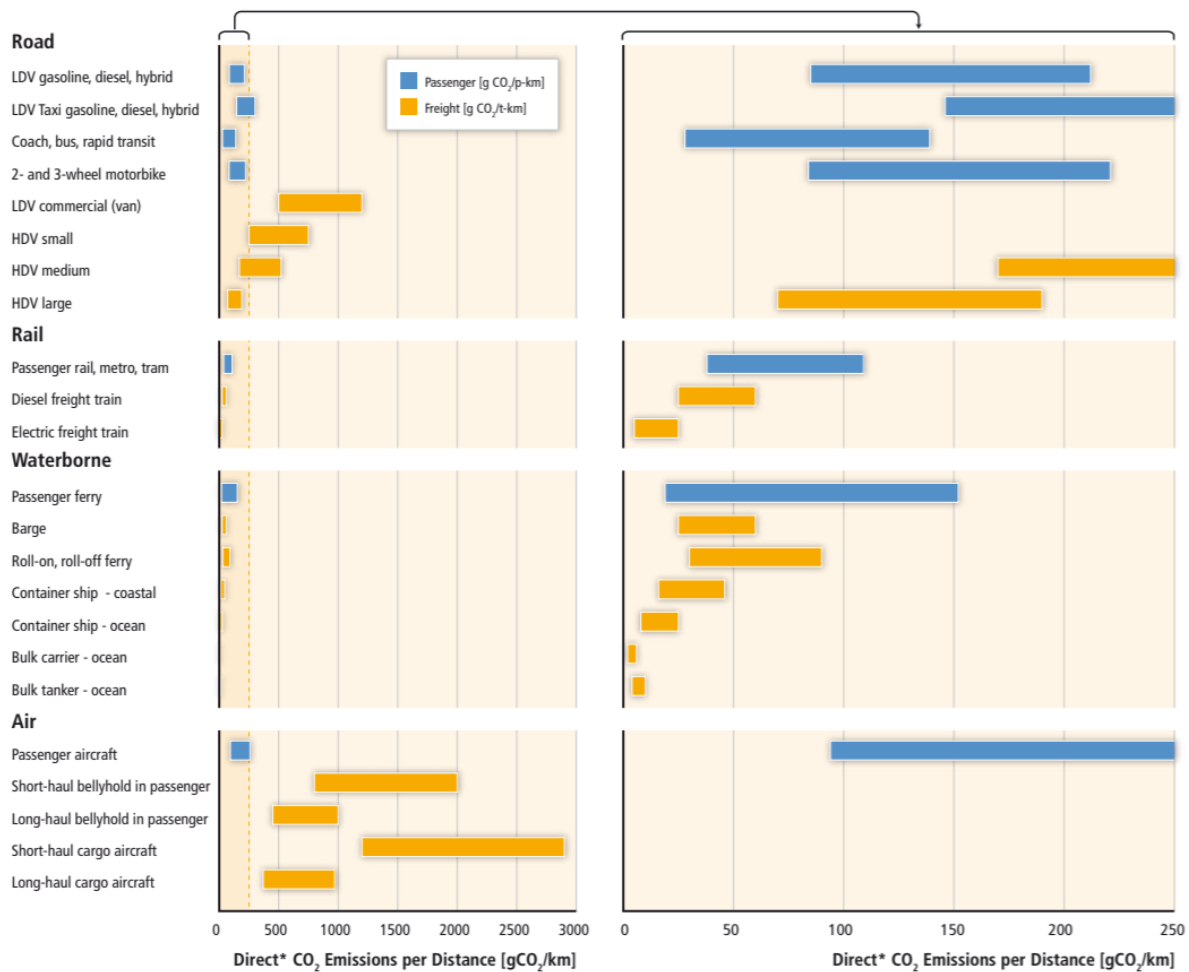


Figure 3. Comparison of g CO₂ emissions per passenger-km and tonne-km between different modes¹²

However, while rail transport is significantly cleaner than its road counterpart, the challenge of decarbonisation remains alive if moving people and goods on tracks also uses fossil fuels. The reduction of external costs from road modes is not as significant for diesel traction as it is for electrically powered trains, especially for passenger services. As Figure 3 shows, despite being generally more sustainable, diesel-powered trains still emit at least twice as much CO₂ in the atmosphere than electric ones.

Our research shows that this is relevant to the Asia and the Pacific region, where only a third of the railway network is electrified¹¹. With that, it logically follows that the majority of the traffic volumes currently carried on tracks are powered by diesel locomotives that still emit greenhouse gases to the atmosphere.

Moreover, improving traction capabilities can also have a positive effect online capacity. In some cases, such as the case study of the dedicated freight corridors in India, lines are currently operated at or above capacity, preventing operators from picking up traffic from road vehicles. In that, decarbonisation efforts carry a double positive in not only removing

direct emissions from trains, but also allowing the railways to draw traffic from more polluting mode

2. Current state of decarbonisation in railway in ESCAP region

The transport sector is responsible for an important share of the overall carbon emissions, but contrary to other sectors, emissions are not ceasing sufficiently rapidly to prevent irreversible damage caused by climate change¹⁵. It is not surprising that ambitious targets in policy and regulation are being agreed at a global scale, following the overarching Sustainable Development Goals (SDGs).

In Asia, equal efforts can be found to promote the decarbonisation of transport. It is worth mentioning the large scale NDC Transport Initiative for Asia (NDC-TIA), with the objective to decarbonize the transport sector in China, India, Vietnam, and further Asian countries¹⁵. This initiative offers a comprehensive and multimodal look on transport decarbonisation strategies, of which rail plays a part.

Although it is important to note that rail emissions make up a small proportion of overall emissions, this does not mean that railways can afford to be complacent. In most countries in Asia and the Pacific, railways are still powered by diesel locomotives, especially in the freight sector. While the combined environmental impact of railways is currently dwarfed by road transport, rapid technological advancements in the latter mean that the former must act more quickly.

The railway sector has particular challenges to address in terms of decarbonisation and the reduction of its environmental impact. Railways are, in comparison to other modes, particularly costly to build and to operate, even more so if it includes overhead electrification (OHE).

Firstly, the long lifecycle of many railway assets means that drastic changes are not economically feasible. Secondly, the sheer scale of rail infrastructure (in terms of cost, resource, planning etc) means that changes are not easily or quickly realisable. Finally, the disparity in the maturity of railway networks observed in countries across the Asia Pacific region means that there is no one size fits all for decarbonisation roadmaps.

In the ESCAP region, Gross National Income (GNI) per capita, as measured by the World Bank, ranges extensively between US\$556 and US\$60,000. Similarly, Human Developments Indices (HDI) in the region, as measured by the UNDP, range between 0.497 and 0.938. Yet, even though GNI and HDI usually correlate to each other, none of them in fact can be used as a predictor of railway decarbonisation maturity. Figure 4 and Table 1 illustrate the little correlation between economic maturity of a country and the share of railway electrification.

Table 1. Railway electrification in ESCAP countries¹⁶

Country	Total route-km	Electrified route-km	% of network electrified
Afghanistan	92	0	0.0%
Armenia	686	686	100.0%
Australia	33343	3098	9.3%
Azerbaijan	2140	1169	54.6%
Bangladesh	2877	0	0.0%
Cambodia	642	0	0.0%
China	68141	46012	67.5%
Korea DPR	7435	5400	72.6%
Fiji	597	0	0.0%
Georgia	1378	1343	97.5%
Hong Kong, China	334	334	100.0%
India	68155	39866	58.5%
Indonesia	5483	93	1.7%
Iraq	2370	0	0.0%
Iran (Islamic Republic of)	9146	181	2.0%
Japan	19041	11722	61.6%
Kazakhstan	16061	4238	26.4%
Kyrgyzstan	424	0	0.0%
Malaysia	1655	782	47.3%
Mongolia	1814	0	0.0%
Myanmar	5031	0	0.0%
Nepal	59	0	0.0%
New Zealand	4128	506	12.3%
Pakistan	7791	293	3.8%
Philippines	509	0	0.0%
Republic of Korea	4109	2989	72.7%
Russian Federation	85494	44067	51.5%
Singapore	240	240	100.0%
Sri Lanka	1562	0	0.0%
Tajikistan	620	0	0.0%
Thailand	4092	58	1.4%
Turkey	10378	5070	48.9%
Turkmenistan	7680	0	0.0%
Uzbekistan	4735	1830	38.6%
Vietnam	2481	0	0.0%

It can be seen that less than a third of ESCAP countries have their railways mainly operating with electrical traction. Diesel trains, especially in the freight sector, seem to still dominate the landscape in the region. Moreover, as shown in Table 2, freight accounts for the larger share of volumes practiced in the region, with the exception of Japan, South Korea, and the South Asian region. This is an important aspect to take into account since rail freight tends to

receive fewer subsidies and therefore relies on tight margins of financial viability. Where passenger traffic is dominant, such as the case in India, there might be a social justification for government investment.

Table 2. Railway traffic volumes and densities in ESCAP countries

Country	Total traffic volume (million traffic units)	Share of freight traffic volume (%)	Traffic volume density (1,000 traffic units/route-km)
Afghanistan	-	-	-
Armenia	745	92.6%	1086.0
Australia	431076	95.9%	12928.5
Azerbaijan	5696	90.4%	2661.7
Bangladesh	11263	10.9%	3914.8
Cambodia	-	-	-
China	4296760	67.1%	63056.9
Korea DPR	-	-	-
Fiji	-	-	-
Georgia	6157	89.0%	4468.1
Hong Kong, China	-	-	-
India	1899856	38.9%	27875.5
Indonesia	47454	64.3%	8654.8
Iraq	833	88.0%	351.5
Iran	73999	79.4%	8090.9
Japan	466080	4.2%	24477.7
Kazakhstan	377784	94.9%	23521.8
Kyrgyzstan	1739	97.9%	4101.4
Malaysia	3459	33.0%	2090.0
Mongolia	18496	94.0%	10196.3
Myanmar	5048	17.5%	1003.4
Nepal	-	-	-
New Zealand	3857	100.0%	934.4
Pakistan	32983	24.5%	4233.5
Philippines	384	0.0%	754.4
Republic of Korea	101244	7.3%	24639.6
Russian Federation	2736082	95.1%	32003.2
Singapore	-	-	-
Sri Lanka	7534	1.7%	4823.3
Tajikistan	260	89.2%	419.4
Thailand	8582	29.9%	2097.3
Turkey	28966	50.8%	2791.1
Turkmenistan	15667	85.1%	2040.0
Uzbekistan	27245	83.9%	5754.0
Vietnam	7284	51.4%	2935.9
TOTAL	10616533	68.0%	27885.19

One way to understand the feasibility of electrification is to measure traffic densities. Usually measured in the form of 1,000 traffic units (tonne-km + passenger-km) per route-km, it illustrates the intensity that a railway network is used for the transport of cargo and/or passengers. The higher the density, the greater the economies of scale for any investment that aims at reducing carbon emissions. Also, routes and networks that experience high traffic densities may justify the higher costs of electrification. This can be observed in countries with high railway usage such as Japan, China, South Korea, India, and parts of Russia. Some countries where densities are not relatively high but electrification is almost prevalent may be explained by geographic and historical circumstances. Others, such as Hong Kong and Singapore, simply by their sizes, meaning that their railway networks consist of urban systems.

It can also be observed from Tables 1 and 2 that some countries may potentially justify partial or total electrification using traffic densities. Australia is an example, reaching densities over 12,000 traffic units per route-km, also counting with a high GNI. Others, perhaps overlooked, include Indonesia and Iran, where traffic densities reach similar levels to those found in Germany. With a lower degree of certainty, Pakistan, Sri Lanka, and Uzbekistan have similar traffic densities to France, yet different economic indicators.

Other countries still present relatively low traffic densities and may find it difficult to justify electrification before increasing efficiency. Those countries may look at decarbonisation solutions at rolling stock level which can provide cost effective pathways to the later economies of scale that justify more ambitious infrastructure commitments.

3. Case study of the development of a dedicated freight corridor

Indian Railways operates one of the largest networks in the world, with over 68,000 route-km and over 95,000 km of tracks. Following the country's economic growth, the Indian Railways has been upgrading the network substantially with a vision of rail leading the national decarbonisation efforts. Since 2014, the government-owned infrastructure manager has electrified over 40,000 km.

Electrification will reduce (and has the potential to reach zero) emissions from the railway sector. However, decarbonisation could not go further in transferring traffic from road to rail because the network capacity is saturated. Some lines, such as Howrah-Delhi and Mumbai-Delhi, have trains carrying between 115 per cent and 150 per cent of their capacity¹⁷. The mixed use of tracks for passenger and freight services on dated infrastructure hindered the overall performance of the system. From a technological standpoint, operating different rolling stock with different speeds and braking curves can considerably detrimental to the overall capacity on the lines, especially if there are speed restrictions in place caused by poor track condition. From an operational perspective, capacity limitations force services to follow tight timetables that inevitably lead to delays when variations occur.

To support the role of the railways in decarbonisation, Indian Railways decided to invest in the construction of a dedicated freight network. Following the incorporation of the Dedicated Freight Corridor Corporation of India Limited (DFCCIL) in 2006, the company set out an ambitious plan to build six lines alongside the existing Golden Quadrilateral connecting the four main cities in the country (Delhi, Mumbai, Chennai and Howrah). Currently, the existing Golden Quadrilateral comprises 16 per cent of the total network of the Indian Railways, but account for 52 per cent of the passenger traffic and 58 per cent of revenue earning freight traffic¹⁸. However, even with those numbers, the railways lost the share in freight traffic from 83 per cent in 1950-51 to 35 per cent in 2011-12.

DFCCIL network consists of six lines that link the four main cities of India. At present, two lines are under construction, and the others under planning. The two lines that are under construction are the Eastern Dedicated Freight Corridor (DFC), linking Ludhiana in Punjab to Dankuni in West Bengal, and the Western DFC will connect Mumbai with Dadri in Uttar Pradesh. The Eastern DFC will be 1,875 km long, of which 351 km have been inaugurated on 29th December 2020¹⁹, while the Western DFC will be 1,506 km long and first sections are planned to be opened in 2021.

Once the dedicated corridors are fully operational, they are expected to draw up to 70 per cent of the freight traffic of the existing network¹⁴. This equates to almost 520 billion tonne-km per year freed up from the existing network that can be used to shift more passenger and goods from roads and significantly reduce overall emissions from the transport sector¹⁰. A

2011 study on the carbon footprint of the Eastern and Western DFCs found that the two lines could achieve a cumulative reduction of GHG emissions by more than 450 million tonnes of CO₂ in 30 years, compared to a business-as-usual scenario²⁰. The biggest impact is to be found in the Western Corridor, where the ‘no DFC’ scenario emits six times more CO₂ than the scenario with the DFC (Table 3).

Table 3. Cumulative GHG emissions for 30 years (in million-ton CO₂) for each of the corridors under the DFC and No DFC scenarios¹⁷

	Eastern DFC	Western DFC
Freight to be transported under DFC scenario	1,975	3,241
GHG emissions under No-DFC scenario	114	465
GHG emissions under DFC scenario	48	77

These savings are not only significant in terms of the reduction of the environmental impact they promote, but they also contribute to justifying the investment in low-carbon technologies when taking the social cost of carbon (SCC) into consideration. Ricke et al²¹ estimate that the social cost of carbon in India is approximately US\$86 per tonne of CO₂, meaning that in the 30-year span of the comparison, the country saves approximately US\$38.7 billion from the externalities of high-carbon transport. This amount towers over the estimated construction costs of the two dedicated freight corridors at approximately US\$13 billion¹⁶.

In fact, including the social costs of carbon may help decision makers identify corridors that carry significant benefits such as the DFCs in India. The replacement of diesel traction in the railways is a positive start for the decarbonisation of the sector, but it becomes limited if not accompanied with the expansion of network capacity to offer clean alternatives to road vehicles. Should these processes be coupled with low-cost traction solutions, benefits are to exceed costs in much shorter time windows than those studied in India.

4. Low-carbon traction solutions for railway transport

A. Rail electrification and related issues

The case study on dedicated freight corridors in India (annex) has shown the significant potential impact on the reduction of emissions and the increase of operational capacity, it must be noted that electrification may not be a cost-effective solution to some or many ESCAP countries. Firstly, electrification requires a substantial capital investment in infrastructure. The Indian initiative of electrifying 13,675 km of its existing lines will require an estimate of more than US\$1.6 billion²². In other countries, estimates are even higher. For instance, Al-Tony and Lashine²³ estimated that electrifying the Cairo – Alexandria line in Egypt would cost over US\$250,000 per track-km. Much higher costs are found in high-income countries. In the UK sector, for example, costs up to US\$2 million per single track-km are seen as acceptable²⁴.

This alone can establish a barrier for implementation, considering that almost half of the countries in the region are situated in the low-income or lower middle-income brackets of the World Bank²⁵. Furthermore, based on the International Union of Railways (UIC) database¹¹, various countries may not yet operate traffic volumes that could justify such investment. Further cost-benefit analyses are required on an ad hoc basis.

Secondly, the operational costs may not prove cheaper than diesel, considering the cost of energy production and distribution, and maintenance involved. Moreover, the source of energy is an important aspect for the assessment of overall emissions of electric traction. Even though electrified lines are labelled as zero-emission at the point of use, the production of electricity may come from pollutant sources. The International Energy Agency has highlighted that the majority of coal-fired electricity generation is found in Asia²⁶.

Finally, the impact of connecting railway lines to the grid must be considered. An issue that has been highlighted in some Sub-Saharan African countries is the unreliability of power distribution and the considerable energy requirements of operating freight trains. Also, the vulnerability of fixed assets to climate events and vandalism can have a significant impact on the viability of electrification initiatives across the globe.

These challenges may help understand the political and market resistance to move away from diesel traction. Autonomous traction systems are easier to maintain and operate within a transport mode that serves its best purpose over long distances. Until recently, electrification or hybrid systems (diesel-electric) were seen as the only viable alternative to reduce overall emissions from railway operations.

B. Emerging options for railway traction

Recent technological developments have increased the efficiency of other traction systems that are now being developed as potential candidates to help decarbonise rail transport. The two main contenders in the traction domain are battery electric and fuel cell hybrid systems.

Figure illustrates the different powertrain architectures using a variety of traction systems, where (a) shows a fully battery electric system that drives the motor generator, and (b) represents the hybrid fuel cell solution. Architectures (c) and (d) have been found in other hybrid systems that still rely on diesel but add other energy sources to reduce the consumption of the fossil fuel.

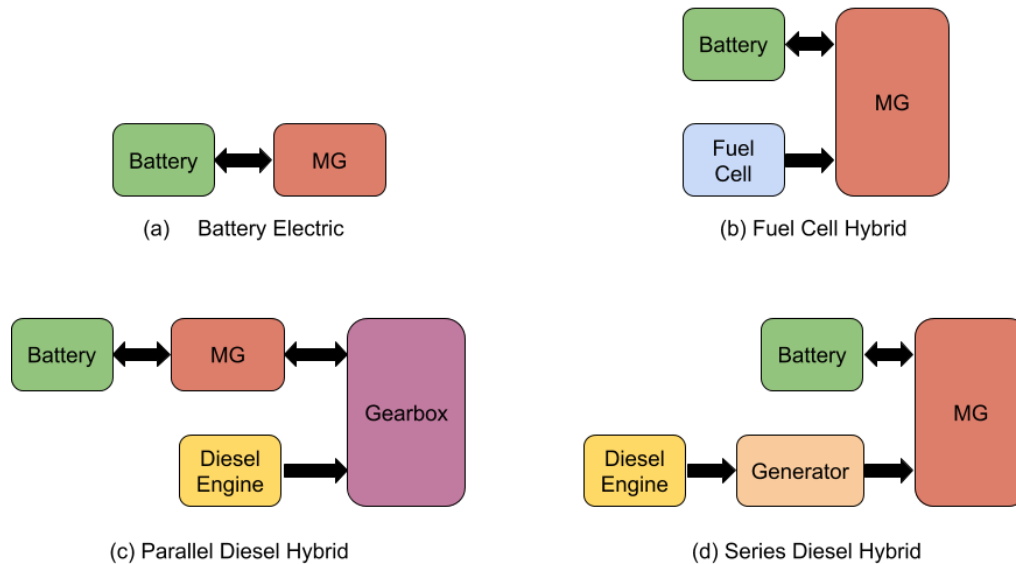


Figure 5. Powertrain architectures. MG stands for electric Motor-Generator. The MG in (a), (b) and (d) is directly connected to the axle, whereas the gearbox in (c) is directly connected to the axle

a. Battery Electric

The emergence of lithium-ion batteries in a variety of global markets has triggered increasing interest in its use for decarbonising transport. The term “lithium-ion battery” does not refer to a single battery chemistry but rather to a wide spectrum of battery chemistries that range from unproven concepts to technologically ready and viable ones. The automotive industry is almost entirely focusing on battery electric vehicles as a means to reduce its environmental impacts. In 2017, global sales of electric vehicles topped one million units for the first time, and in 2019 sales had already more than doubled to 2.1 million vehicles²⁷. In 2019, the sales of electric cars in Norway overtook those powered by petrol, diesel, and hybrid engines²⁸

The recent improvements in energy efficiency and range have also attracted government and industry to explore the use of electric batteries in public transport systems. Four countries (Finland, India, China, and Chile) have successfully rolled out battery electric buses in major urban areas, with ranges reaching almost 200km²⁵. Despite initial rollouts in various countries, 99 per cent of the global electric bus fleet is in China²⁹

In the railway sector, purely battery electric operation is slowly finding its way through technological development. Railway operations present some challenges to battery systems in that the distances travelled by a service can surpass 1,000 km, not to mention the much greater loads carried. The resulting system therefore requires a large amount of batteries to produce enough traction for a freight train. For instance, the prototype locomotive developed

by GE Transportation and BNSF has a battery storage unit containing 20,000 cells to produce 4,400 horsepower³⁰. This is a considerable improvement in applications where battery electric locomotives have mainly been used in maintenance work when electrified overhead lines are unavailable.

The possibility of running trains with autonomous traction that does not emit any component in the atmosphere is perhaps the most attractive feature of battery electric trains. Nonetheless, there are important considerations on its use and feasibility. The first and most prominent concerns the sustainability of using a non-renewable material such as lithium as a main energy source. Considering that diesel has almost 100 times the energy density of lithium-ion^{31,32}, powering trains with batteries would require a considerable amount of the material, at the expense of space and weight. Furthermore, it is impossible to achieve a comparable range to that offered by diesel traction.

There are two main drawbacks with the use of batteries at both ends of their life-cycle. There are important social and environmental impacts associated with the production of lithium-ion batteries. It takes 250 tons of the mineral ore spodumene, or 750 tons of mineral-rich brine to produce one ton of lithium³³. The process is water-intensive. In the Salar de Atacama in Chile where lithium is produced, 65 per cent of the region's water is consumed by mining activities³⁴.

Disposal is another concern. So far, there is no established process for recycling lithium. It logically follows that, should none be developed, there will be severe environmental impacts in a few decades when the life cycle of current batteries reaches its end³¹. The non-renewable nature of battery materials currently approximates the solution to fossil fuels as it requires measures to deal with end-of-life by-products. There is also the geo-political matter of localised production attached to non-renewable sources. Lithium is found in some a few countries, and the market exploitation of this natural resource may lead to similar geo-political dynamics to that of oil in the 20th century.

From an operational perspective, battery electric trains are classed as autonomous traction systems, meaning that they do not rely on line side infrastructure. This reduces overall capital and operational costs. On the other hand, there are some constraints in its use. Firstly, there is the physical requirement of battery units to produce enough power to propel a train consist. To rival the energy stored in a 6000 litres diesel tank typical of diesel freight locomotives, a lithium-ion battery would weigh 107 tons and occupy a volume of 71,000 litres, which is 21 and 12 times greater than diesel respectively.

In long distance services, battery electric trains would either need to be shorter consists, use multiple locomotives, or they might require recharging points, otherwise the weight and size of battery units required may prove unfeasible. The locomotive being developed in the United States is meant to cover 560 km with added charges from regenerative braking. Considering that electric buses require between three to four hours to recharge fully, longer lines may require changing locomotives at stations.

Battery powered trains may remain an alternative for non-electrified sections of track in electrified lines. Bombardier has trialled a battery powered tram capable of 41.6 km of independent movement in Germany, and in Birmingham, UK trams are battery powered for a short catenary-free section³⁵. Vivarail have recently claimed their battery trains can travel up to 160 kilometres and recharge in 10 minutes, although such a train has yet to enter service. More locally, some research has been conducted into the possibility of using battery-powered commuter trains in Tanzania³⁶.

b. Fuel Cell Hybrid

In recent years hydrogen has regained prominence as a fuel source because it is, or at least it can be, an essentially carbon free solution. Its development as a contemporary fuel source seems to progress equally in the automotive and the railway sectors, with mature implementation cases on the latter.

The fuel cell hybrid architecture (b) is a series hybrid architecture that powers the train using batteries and fuel cells. Similar to other systems, it stores recuperated regenerative braking energy into the battery. Various fuel cell technologies are available but the polymer exchange membrane fuel cell (PEMFC), which runs on hydrogen, is currently the most suitable and technologically ready for vehicular traction applications³⁷.

Hydrogen fuel cell systems are perhaps the cleanest form of traction because it produces water as a by-product. These fuel cell systems generate electricity which is converted from the chemical energy of hydrogen and oxygen, and differently from a battery, can do so indefinitely as long as fuel and oxygen are supplied. What defines the carbon footprint of hydrogen fuel cell systems is the way that the hydrogen used in the process has been produced. To be essentially carbon free (labelled as green), energy production must be achieved using renewable sources. Conversely, hydrogen produced from carbon-emitting sources is labelled as brown (or blue if the carbon is somehow offset).

Fuel cells can be a competitive alternative to diesel because they have a significantly longer fully charged range than battery electric trains due to the higher energy density of hydrogen. For example, the Siemens Mireo Plus H claims a range of up to 1000 km³⁸. In comparison to the previously cited battery solution of 107 tons and 71,000 litres, a rivalling 700 bar hydrogen storage solution would weigh 15.2 tons and occupy a volume of 40,000 litres.

Currently, fuel cells are being used to power catenary-free tramways in China and Qatar^{39 40}. Significant progress has been made in Europe, where the first hydrogen passenger trains in the world has been ordered for regional services in Germany⁴¹. Spain and Italy have also placed orders on regional fuel cell trains^{42,43}. Moreover, a partnership in the UK has developed the first retrofitted hydrogen fuel cell train from an electric multiple unit passenger train⁴⁴.

While implementation is on track for passenger lines, the use of hydrogen fuel cell systems in freight operations is still under development. Like battery electric systems, the challenge for hydrogen fuel cells lies in the energy density compared to diesel. Storing the same amount of

energy as a 6,000-litre locomotive would take almost two tonnes of hydrogen, or around 267 W322N tanks⁴⁵. Fuelling stations, for smaller quantities of hydrogen, may be supplied economically by tube trailers filled from a central hydrogen facility in regions with robust logistics infrastructure. However, this may prove difficult in places where road access is not good, unless the hydrogen can be supplied by rail, or produced locally.

Compared to battery electric systems, hydrogen fuel cells do not carry social and environmental concerns regarding end-of-life management and disposal. On the other hand, using hydrogen as a fuel requires a supply chain in place. This means that operating hydrogen fuel cell trains need existing hydrogen production capability locally, as well as the logistics to supply the fuel to filling locations along the railway network. Hydrogen is currently more expensive than diesel, but the relative prices may change drastically when economies of scale are achieved with increased production, and the internalisation of fossil fuel externalities are added to its costs.

There is no one size fits all for decarbonisation solutions in railway freight. Unfortunately, the operational, technical, and commercial viability of decarbonisation strategies will differ among the various railways in the region. This is due to the distinct traffic densities, climate, economic and social structures, and geo-political dynamics.

Electrification has been the most established pathway to decarbonising railway operations in countries where the costs can be justified by the high passenger/freight traffic volumes and has been a successful endeavour in countries like India that have high freight demand. However, it is an expensive measure that only countries in the higher income brackets may be able to afford.

C. Pros and cons of the alternative traction solutions and way forward

Of the alternative traction solutions, battery electric systems currently have a lead in terms of maturity, but hydrogen fuel cells may prove a more robust alternative to diesel traction systems. In the freight sector, battery electric trains are making their way to testing, while the development of hydrogen fuel cells is still under development. However, the greater range, the possibility of being essentially carbon free, and the fully renewable nature of the fuel can make hydrogen more advantageous.

There is still a cost issue with both alternative traction systems. Both low-carbon systems (battery electric and hydrogen fuel cell) are still more expensive per energy unit than diesel, and both still need considerations to overcome the much lower energy densities. However, the price difference is expected to reduce, or even invert, when economies of scale are achieved, and the externalities of fossil fuels are fully inserted in the costs of their supply chain.

At early stages of implementation, political will and the right policies are crucial to decarbonisation. It is unlikely that market forces will direct the transition in the direction of decarbonisation and within the necessary timescale unless there is governmental support to establish alternative pathways.

Least developed countries may have the most relevant markets to alternative traction systems. That is because high-income countries, or countries that already count with high traffic volumes across the railway network, may be able to justify traditional electrification. Conversely, lower income countries or those with lower traffic volumes may not have the financial incentives to pursue full electrification and therefore adopting alternatives can support their development while successfully contributing to the overall decarbonisation of the transport sector in the region.

5. Decarbonisation opportunities for railways in the region

There are several ways to reduce carbon emissions from railway operations, of which overhead electrification is the most common. As explained in the previous chapter, electrification has been widely implemented across the world, mostly in nations with more developed economies, where railway traffic is sufficiently large to justify the costly investments. Nonetheless, the social, economic, and environmental impacts of GHG emissions are felt globally and irrespective of economic advancements, which in turn calls for more cost-sensitive options to achieve similar results. This section briefly lists some of the options for decarbonising railways in face of their effectiveness, costs, and feasibility.

A. Overhead Electrification

What is it?

Overhead electrification (OHE) involves installing overhead wires (known as catenary) to supply electrical power to trains.

How does this achieve decarbonisation?

As the trains are electric, there are no emissions at the point of use, and with renewable electricity input, there is the potential for a completely zero emission system.

How effective is the decarbonisation?

The overall emissions released are largely dependent on the electric grid's mix of power sources⁴⁶, which makes it a suitable decarbonisation candidate for countries with plenty of low-carbon base-load power sources, e.g., hydro and nuclear energy. It should also be noted that the catenary is responsible for the biggest share of rail infrastructure greenhouse gas emissions⁴⁷.

How costly is it?

The catenary necessary for OHE is typically very expensive⁴⁸. Installing catenary is also a large infrastructure project which should be treated with caution; for example, although the upgrade of the Great Western Railway in the UK was still considered to have a promising benefit to cost ratio, the nature of such projects involves infrastructure operators, government departments, as well as rolling stock parties. Confusion between these, and failure for various parties to plan their parts of the project adequately, led to an increase in cost of £1.2 billion over the original estimated £2.1 billion, a reduction in scope, and a delay of over 18 months⁴⁹.

How feasible is it?

As mentioned above, this largely depends on the capability of the country in question to fund and manage large infrastructure projects, the existing energy mix, and whether such a

project would be justified; for large traffic volumes, electrification can be a sound investment, but this is not the case for lower traffic volumes.

B. Biodiesel

What is it?

Biodiesel is diesel fuel which scales back the diesel derived from petroleum sources (petroleum-diesel) and blends it with waste animal or vegetable fats⁵⁰.

How does this achieve decarbonisation?

This reduces the emissions of the overall system because the crops producing vegetable fats take in CO₂ while they grow. It also reduces the reliance on non-renewable resources. However, Biodiesel is only considered cleaner than pure petroleum-diesel if the organic fat is derived from waste streams, as the carbon stored in the waste was bound to be emitted by means of natural decomposition.

How effective is the decarbonisation?

The ratio of organic fat to petroleum-diesel mandates biodiesel's decarbonisation effect. Current diesel engines are only compatible with up to 10% biodiesels (10% organic fat and 90% petroleum-diesel), which limits the environmental benefits of this fuel.

How costly is it?

This is the easiest and quickest option, as the existing infrastructure to service diesel trains can be retained.

How feasible is it?

For many countries it will be possible to introduce this fuel relatively easily. However, its decarbonisation benefits may be limited if the fuel must be imported over a great distance, and so it may not be a feasible route to decarbonisation.

C. Batteries

What is it?

Battery powered trains are electric trains which store electrical energy in batteries on board.

How does this achieve decarbonisation?

Just like with OHE, there are no emissions at the point of use, and with renewable electricity input, there is the potential for a completely zero emission system.

How effective is the decarbonisation?

As with OHE, this will depend on the source of the electricity. However, because batteries are generally used for smaller scale systems, it may be possible to use greener micro grids.

How costly is it?

Although this solution is much less costly than OHE, the batteries have a limited cycle life, which may vary considerably depending on the use case⁵¹. This will affect how often they need to be replaced which changes the cost.

How feasible is it?

The low energy density limits the useful travel range of battery-powered trains which is around 100km, and so they are only suitable for low volume, short distance routes, or for short extensions to OHE routes.

However, a successful battery-powered train trial has been performed in the UK⁵², and Birmingham's tram system also uses batteries every day⁵³. There is no reason to believe a trial would not be successful in the region, provided the charging infrastructure is in place. The lack of this charging infrastructure has previously been a barrier to Electric Vehicle (EV) adoption on the roads⁵⁴.

D. Hydrogen

What is it?

Hydrogen-powered trains use a hydrogen fuel cell to combine hydrogen fuel on board the train with oxygen from the air to create electricity. As hydrogen is more energy-dense than batteries, this allows for longer distances to be covered.

How does this achieve decarbonisation?

A hydrogen fuel cell produces no emissions, and so this system produces no emissions at the point of use.

How effective is the decarbonisation?

The effectiveness of hydrogen as a decarbonisation method depends on the source of the hydrogen. Green or blue hydrogen can be produced with no emissions, making the whole system decarbonised, but grey and brown hydrogen produce considerable emissions in their production. However, the establishment of a hydrogen infrastructure, even with grey or brown hydrogen, can be seen as a steppingstone to full decarbonisation.

How costly is it?

For lower volume routes, hydrogen offers a much less costly option than OHE as it does not require the catenary. It should also be noted that there are wider benefits; The International Energy Agency, in a 2019 report⁵⁵ identified considerable scope for hydrogen to be produced using renewable energy at low cost across the region. The same report also highlighted that stimulating demand for hydrogen can be a key part of starting the hydrogen

economy; thus, a hydrogen railway scheme could act as a springboard for other decarbonisation projects.

How feasible is it?

Although there have been concerns about hydrogen in a railway vehicle context ^{56,57}, there have been numerous successful demonstrations of hydrogen rail vehicles^{58,59,60}. As mentioned earlier, the success of any hydrogen powered rail system will depend on the supporting hydrogen infrastructure.

E. Doing Business

Although the vast majority of railways and operators in the region are nationalised, many of the technologies mentioned here will not be indigenous to the country. For example, although Horizon Fuel Cell are based in Singapore⁶¹, many of the fuel cell stacks used in transit buses are produced by Ballard ⁶², who have bases in various locations, only one of which is in Asia ⁶³ and many other manufacturers are based in Europe ^{64 65}.

Therefore, it is of some importance that these manufacturers are able to do business in the country where decarbonization is taking place.

The World Bank Group compiles global ease of doing business data⁶⁶. This report identifies several reforms countries may institute to increase the ease of doing business, including construction permits, access to electricity, the ease of registering property, the ease of acquiring finance, the ease of paying taxes, and the ease of cross-border trade.

It should be noted that according to the report, almost all of the countries considered in this report have improved their ease of doing business in at least one of these categories; of particular note is the increasing digitisation of many government services across the region.

6. Decarbonisation Maturity Assessment

The decarbonisation of railway networks depends on a multitude of factors that go beyond the availability of infrastructure and/or traction systems.

To establish a sustainable pathway to decarbonise rail operations, additional aspects within the political, economic, and regulatory domains must be aligned properly.

One way to assess countries in their current status on the decarbonisation roadmap makes use of maturity matrices to measure progress in each capability.

The table is organised logically in that the columns represent the capabilities associated with decarbonisation, and the rows indicate the level of maturity in that capability.

For the specific context of railway freight transport, four general capabilities were identified, measured across four maturity levels.

This offers a strategic tool for decision making that looks at the functional and policy aspects rather than focusing on specific solutions and/or systems.

The resulting table established a strategic grid that understands the equal importance of each capability in achieving and maintaining a sustainable decarbonisation programme.

The resulting maturity matrix illustrated in Table 4 evidences the complexity of decarbonisation pathways in that reducing emissions from railway freight is not necessarily the same of a simple electrification programme.

There are other capabilities to be addressed so that railways can run either on electricity or alternative traction, ranging from fuel and power supply to regulation and financial incentives.

Such table sets the foundation to particular roadmaps, against which each nation can be plotted and measured in every capability.

From a logical standpoint that a top maturity of 4 is sought, countries can easily identify the capability gaps in each column between their current state and the end goal.

This process highlights that decarbonisation is a step process rather than a radical leap.

Table 4. Maturity matrix of railway freight decarbonisation

MATURITY LEVEL	CAPABILITY			
	Electricity Supply	Supporting Infrastructure	Finance & Investment	Governance & Management
	4 <ul style="list-style-type: none"> ➤ Electricity supply completely zero emission ➤ Supply infrastructure modern and efficient ➤ Substantial access available universally, even in remote areas 	<ul style="list-style-type: none"> ➤ Zero emission infrastructure near universal ➤ Any remaining hydrocarbon use from renewable sources 	<ul style="list-style-type: none"> ➤ Rail infrastructure investment seen as a high government priority ➤ Private finance readily available for rolling stock ➤ Public finance available for a wide variety ➤ Ease of doing business high 	<ul style="list-style-type: none"> ➤ Decarbonisation seen as a high management priority ➤ Continual improvement cycle for decarbonisation implemented ➤ Rolling stock modernisation given high priority
	3 <ul style="list-style-type: none"> ➤ Large component of zero emission supply ➤ Supply infrastructure reasonably efficient ➤ Supply access universal in most areas 	<ul style="list-style-type: none"> ➤ Substantial zero emission infrastructure ➤ Renewable sources of hydrocarbons in the mix 	<ul style="list-style-type: none"> ➤ Rail infrastructure investment seen as somewhat of a government priority ➤ Private finance an option for rolling stock ➤ Public finance an option for many projects ➤ Middling ease of doing business 	<ul style="list-style-type: none"> ➤ Decarbonisation on management radar ➤ Periodic improvements in decarbonisation targeted ➤ Rolling stock modernisation sometimes a priority
	2 <ul style="list-style-type: none"> ➤ Some zero emission sources in energy mix ➤ Supply infrastructure not particularly efficient ➤ Supply access common but not universal (capacity limited) 	<ul style="list-style-type: none"> ➤ Some zero emission infrastructure ➤ Hydrocarbons predominantly from non-renewable resources 	<ul style="list-style-type: none"> ➤ Rail infrastructure investment on government radar ➤ Private investment rare ➤ Public finance scarce for many projects ➤ Middling ease of doing business 	<ul style="list-style-type: none"> ➤ Decarbonisation rarely considered by management ➤ Only very occasional improvements in decarbonisation mentioned ➤ Rolling stock modernisation only addressed occasionally
	1 <ul style="list-style-type: none"> ➤ Few, if any, zero emission sources in energy mix ➤ Supply infrastructure inefficient and outdated ➤ Supply access patchy (very limited capacity) 	<ul style="list-style-type: none"> ➤ All trains fuelled by hydrocarbons ➤ Hydrocarbons from non-renewable sources 	<ul style="list-style-type: none"> ➤ Rail infrastructure investment not considered by government ➤ Private investment almost unheard of ➤ Public finance very rare ➤ Ease of doing business low 	<ul style="list-style-type: none"> ➤ Decarbonisation not considered by management ➤ Improvements in decarbonisation extremely rare ➤ Rolling stock modernisation extremely rare

Electricity Supply

Despite not being under the control of the railway authorities, this is one of the most important components of rail decarbonisation; if electrification is chosen, it is obvious that there must be a sufficiently capable grid to support it, but other decarbonisation efforts (such as green hydrogen or battery charging) will also require electricity.

Most ESCAP countries enjoy very high (if not absolute) access to electricity by their populations, which can illustrate robust generation capacity at a first glance⁶⁷. However, there are two important aspects that determine the maturity of electricity supply for railway decarbonisation.

Firstly, there is the matter of capabilities in energy generation. This issue can be overlooked by the relatively low share of electricity consumption in high-income countries, where it hides the high absolute demand for electricity of railway operations. For instance, the German railway network (41,000km) consumes approximately 25TWh of electricity per year, averaging 0.61 GWh per route-km yearly⁶⁸. If an equal requirement is projected for ESCAP countries (Figure 6), some may not have enough generation capability at the moment for supplying electricity to the railway network. Some extreme examples include Cambodia and Myanmar, where a theoretical electrification of the network would require the equivalent of 40% of the national generation capability. In practice, the realities experienced in other countries support such concern. In order to enable the construction of an electrified Standard Gauge Railway (SGR) network, the country borrowed US\$1.8 billion to increase the national electricity generation capabilities⁶⁹

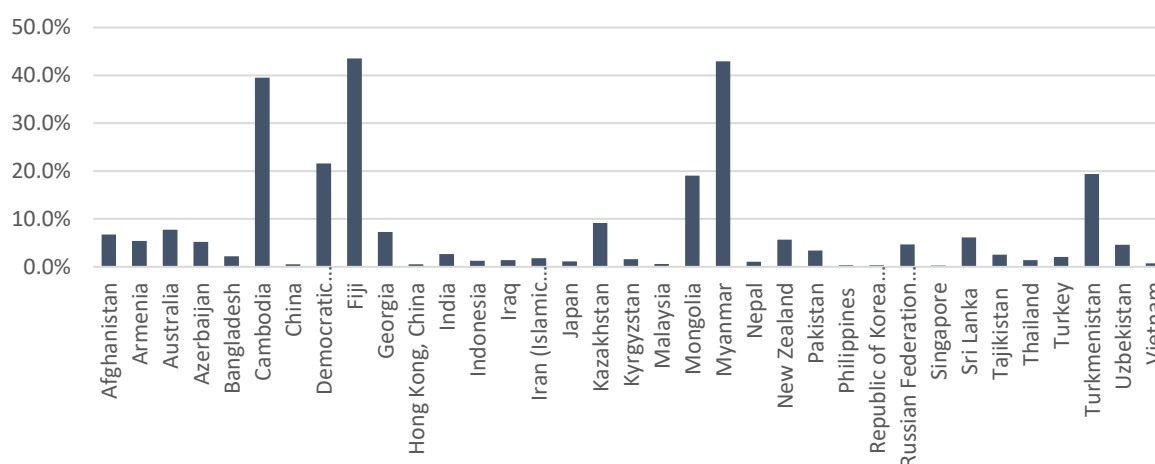


Figure 6. Projected electricity requirements for the railway network as % of national generation capability⁷⁰

Secondly, there is the issue of the source of electricity for railway operations. As much as railways can be zero-carbon from a traction perspective, many ESCAP countries still rely on non-renewable sources in their electricity mix. As Figure 7 shows, there is significant variance in the use of renewable sources between ESCAP countries. These are unrelated to economic

maturity, and are potentially more related to geography and governance. Nonetheless, the use of green electricity is crucial to the decarbonisation of transport, not only in railway electrification but also in the production of alternative fuels such as hydrogen.

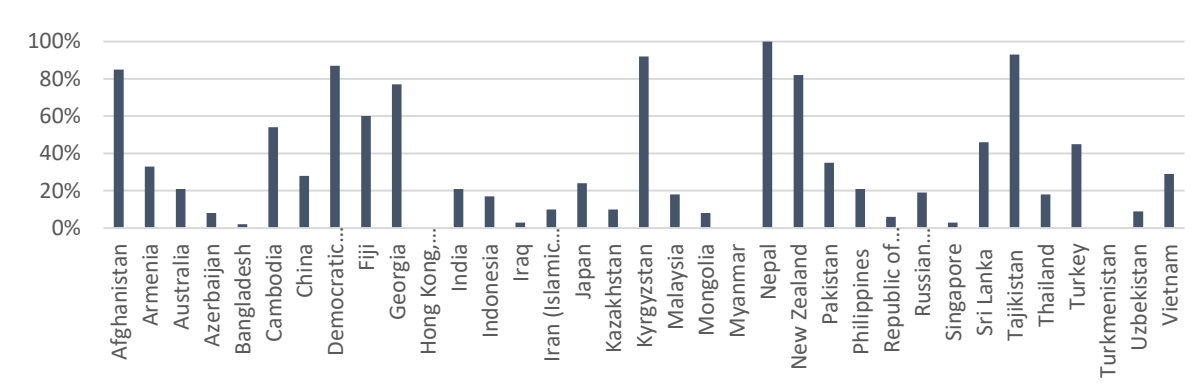


Figure 7. Share of renewables in the electricity mix in UN ESCAP countries with railways⁷¹

Supporting Infrastructure

Discussions over infrastructure costs mainly focus on electrification, but it is perhaps less obvious that hydrogen or battery-powered trains also require supporting infrastructure quite different from current practice. Overall, electrification infrastructure is more widely discussed because of the magnitude of projects and the resources incurred in the process. In a nutshell, electrifying railways requires the construction and maintenance of equipment along the lines.

Electrified railways require a form of power supply to the rolling stock, which can normally be done in the form of overhead wires, third rail, or fourth rail. Overhead lines, as the name suggest, involve a pantograph collecting power from catenaries supported by pylons along the line. In the third and fourth rail options, the power supply is positioned at ground level on the side of the tracks, and a collector shoe is attached to the bogies for power supply.

Electrification is a highly efficient way of powering railway operations, especially in busy lines where greater acceleration is required or in populated areas where exhaust emissions need to be curbed. However, it involves the complexity and complication of managing a number of system interfaces. These include the contact between pantograph and catenary or between collector shoe and third/fourth rail, which are subject to intense forces during the movement of rolling stock. Moreover, the supply of electricity depends on power stations to ensure the steady supply, and all of those are also subject to different standards. Countries adopt different voltages which may challenge interoperability between lines and rolling stock.

Other traction systems, such as batteries and hydrogen, are not entirely free from infrastructure. As in traditional diesel-powered trains, the power is generated by the rolling stock and therefore does not require power infrastructure. However, hydrogen is a fuel and may need refuelling stations especially in longer routes. This would require not only the infrastructure capability to produce hydrogen at large scale, but also a robust distribution network that currently takes the form of pipeline networks to supply enough filling stations.

As hydrogen does not yet achieve the same efficiency as electricity, more filling stations may be necessary.

Finance & Investment

It goes without saying that new, lower carbon equipment will require investment. Where this investment comes from depends on a number of factors, but in many cases government support will be necessary, particularly where there is little commercial incentive. However, private investment should not be overlooked. In some cases, particularly where existing equipment is old, labour intensive and/or expensive to operate, there may be a case for private investment in newer, more environmentally sound equipment. In either case, if decarbonisation is to be pursued, it must be seen as an objective of the investment rather than merely incidental to other factors.

Railways are costly to build, operate, and maintain, yet can produce significant economies of scale under the right circumstances and when made efficient. There are a number of different models in place to finance the railway sector, ranging from fully publicly operated to fully privately operated.

While segregated models (in the form of concessions, franchises, or open access) are argued to produce greater economic efficiency, there is debate whether they can achieve decarbonisation targets within existing incentives and regulations. The transition to zero-carbon railway infrastructure requires an overhaul of rolling stock, trackside infrastructure, supporting energy and power provision, or all combined. Therefore, governments must decide whether these comprise strategic goals that justify public investment, or devise appropriate incentivisation schemes that attract private investment to innovate in the sector.

Governance & Management

The management of the railways themselves have a key role to play in any decarbonisation effort. Performance management often consists of a cycle of plan, do, and review (particularly common in local government) ^{72 73}, informed by data known as KPIs, or Key Performance Indicators. It is an old adage in the UK that “what gets measured gets managed”. Thus, if the management of a railway are not measuring decarbonisation objectives, they are unlikely to make much progress. Therefore, management needs to set objectives concerning modernisation and thus decarbonisation. These objectives could be based on numerous KPIs, such as:

- Diesel fuel usage
- Carbon emission data (if available)
- Age of rolling stock (particularly locomotives)

That type of governance is essential to maintain a balanced and cohesive development in the ESCAP region that comprises several border-crossing routes. Data collection, regulation, and

reporting policies must be in place to ensure a coherent set of measures for regional and international benchmarking against Sustainable Development Goals (SDGs) and sectoral performance targets.

7. Analysis of maturity assessment for selected ESCAP countries

The rail decarbonisation would depend on the following factors:

- Mix of sources in the electricity grid. This is important because the carbon emissions of the electricity needed for various systems has a big impact on the decarbonisation effects of the system
- Freight volume. This is important because some railways with large freight volumes will see more benefit from the considerable expense of OHE, whereas for others the benefits may not be worth the costs
- Local resources. In some cases, local resources may play a key role. For example, natural gas may prove a springboard for the deployment of hydrogen

The countries discussed in this section, namely China, Indonesia, India and Russia could prioritise overhead electrification before other propulsion options because they fulfil the prerequisites of:

- a. low-carbon grid with a combined share of hydro and nuclear power in excess of 30 per cent
- b. high traffic volume densities (over 8,000 traffic units per route-km)

If this is to be pursued, it is suggested that a whole system approach is taken; this will include expertise in catenary, electricity supply infrastructure, and rolling stock. This would avoid the confusion described in section 2, concerning the Great Western scheme in the UK.

It is worth mentioning that these conditions are observations made on the national level. Not all freight routes within these nations are necessarily ideal overhead electrification candidates because some routes might be geographically too distant from clean power sources and some routes might carry only low volumes. For the routes that do not fulfil these conditions we offer the following alternative strategies.

Firstly, hydrogen could be prioritised after overhead electrification in such countries as China and India due to the availability of intermittent renewable sources such as wind and solar in these countries. The hydrogen fuel is ideally to be produced by electrolysis using excess renewable energy, what is called green hydrogen.

Secondly, for some countries such as Russian Federation and Indonesia to invest in hydrogen trains due to the local surplus of natural gas⁷⁴, which can be used to produce either brown or blue hydrogen. Although the environmental merit of these forms of hydrogen are questionable in comparison to green hydrogen, this approach offers a gateway for green hydrogen should it become available in these countries in the future.

Thirdly, battery propulsion is recommended for shorter routes that do not exhibit the traffic volumes feasible for overhead electrification. These routes typically run between mines and shipping ports.

Lastly, countries with an established biomass supply chain such as China, Indonesia and India could consider switching to biodiesel in the interim until their long-term decarbonisation strategies materialize.

Japan, South Korea and Turkey all have promising grid mix but do not currently move enough freight by railway to justify 100 per cent overhead electrification. Strategies and plans to shift modes would potentially be justifiable.

Japan, South Korea, Thailand and Turkey could consider prospects for green hydrogen given their current installations of intermittent renewable energy. As a matter of fact, Japan⁷⁵ and South Korea⁷⁶ have already started public investment in a hydrogen infrastructure for a hydrogen economy.

Such countries as Azerbaijan, Islamic Republic of Iran, Kazakhstan, Malaysia, Myanmar, Philippines, Turkmenistan, Uzbekistan, Vietnam have potentially good gas reserves. Therefore, these countries could invest in brown and blue hydrogen as discussed earlier until green hydrogen becomes a widely available commodity.

Alternatively, countries like Azerbaijan, Malaysia, Philippines and Thailand can relatively quickly switch to biodiesel due to their ready access to a local biomass supply chain.

Lastly, the railways of Bangladesh, Japan, South Korea and Sri Lanka predominantly serve passenger services instead of freight. As such, a holistic decarbonisation strategy needs to consider whether passenger and freight services share the same railway lines and traffic volume should constitute for both type of services.

If a strategy not based on OHE is to be considered, the systems approach should not be abandoned. Although less infrastructure is required, the supply chain must be in place to support any new system, particularly for hydrogen where the supply chain is relatively new.

Further, regulation must keep pace with technological developments. While for OHE, the technology has been widespread in the region for many decades, for hydrogen and battery vehicles this is not the case. Provision should be made for the safe operation of hydrogen-fuelled rail vehicles; this should take into account the risks inherent in the system, but not be so restrictive so as to prevent their use entirely.

8. Factors affecting decarbonisation decisions for rail

Decarbonising transport, and railways in particular, is no easy task because of the many stakeholders involved, who may have competing incentives at time. In addition, the general financing models of railways provide little incentive for large scale investments in zero carbon technologies.

It is important therefore to understand the various factors that affect successful decarbonisation pathways for rail freight. As shown on Table 5, there are both endogenous and exogenous factors to be considered. The more aligned these are, the more successful decarbonisation can be from a socio-economic perspective.

As mentioned before, affordability is a critical component of decarbonisation so that appropriate infrastructure and technologies can replace existing carbon-intensive fleets. In turn, that depends on efficient financing models, as well as a robust industry to support an economical supply chain. On the other hand, exogenous factors in the form of policies, incentives, subsidies, and regulation play an important part. Without appropriate calculations of the cost of carbon (usually referred to as Social Costs of Carbon), cost-benefit analyses will almost always point towards the more pollutant but less infrastructure heavy road transport.

Table 5. Examples of factors affecting decarbonisation decisions for rail

Endogenous	Exogenous
Industry structure	National climate change targets: extent and pace of change
Policy framework for carbon reduction	Policy framework for carbon reduction
Franchise requirements	Funding for rail decarbonisation improvements
On-site renewable energy generation	National freight strategy
Economic appraisals of traction options	Decisions on regional and national hydrogen generation, storage and distribution
Costs of electrification of segments of varying technical difficulty	Availability of batteries of suitable technical specifications
Cooperation and collaboration with road and other transport sectors	Carbon grid mix
Incentivisation for procurement of zero / lower lifecycle carbon traction vehicles	Availability of sustainable biofuels for rail
	Decarbonisation of road passenger and freight traffic
	Cost of diesel fuel for the rail industry

In addition, the full decarbonisation of railway freight also depends on exogenous infrastructure factors such as the national electricity mix. Without appropriate efforts to generate electricity (to either power trains or produce alternative fuels) using renewable sources, full decarbonisation will not be achievable. That includes both endogenous and exogenous factors to be addressed, such as feeder infrastructure (endogenous) and national and regional policies on grid mix (exogenous). The terms brown, blue, and green hydrogen highlight the different levels of decarbonisation of a same fuel that is zero carbon at the point of consumption. The same with battery technologies, where life cycle regulations are crucial to the protection of environmental and social sustainability.

Finally, and highly relevant to the ESCAP context, there is the important aspect of regional policy cohesion and technological interoperability. Rail freight tends to travel across borders, and efficient decarbonisation requires joint approaches to tackle both endogenous and exogenous factors.

9. Recommendations

This report looked at pathways for decarbonising rail freight in the ESCAP community, using a combination of literature review, maturity assessment, and analysis of potential technology solutions. While the region has initiated ambitious efforts to decarbonise transport, it is understood that further activities may be required to achieve positive outcomes in the challenges that the rail sector currently faces.

Railways are still responsible for only a small share of the overall emissions of the transport sector, yet their impact are non-negligible. More importantly, we find that decarbonisation of the railways in the Asia and Pacific region will not be achieved using a “one size fits all” solution. Instead, the solution will depend on numerous factors, from both within and outside of the railways themselves.

In conclusion, we provide the following recommendations for consideration of member countries:

[Develop a maturity assessment for railway freight decarbonisation in the region](#)

Decarbonisation initiatives depend on certain operational, economic, technological, and political structures to be achieved and sustained. We have highlighted the main components, setting a foundational framework for evaluation. The process is also valuable to cluster countries according to certain criteria, such as electricity mix, traffic volumes, share of freight transport, financing models, etc. The maturity assessment can then be conducted to any country of cluster within the ESCAP community to highlight the distance between the current state and the future goals of the sector. Such process will establish the quick wins as well as inform areas where greater efforts are required.

[Develop and agree on targets for decarbonization at regional / sub regional level](#)

This takes into consideration the maturity of each country or sub region and the technologies available. For instance, countries with high traffic densities may be able to look into electrification of the busiest routes, while countries with lower traffic densities may seek alternative traction systems to reduce emissions from operations.

Building on certain traffic volume data, if available, it will be possible to analyse strategic interventions and the necessary steps to lay the foundations to a sustainable decarbonisation paradigm that maintains economic viability of the routes.

With available data, countries may set five yearly targets for the reduction of diesel consumption (endogenous factors) together with the decarbonisation of the energy mix (exogenous factors). These provide key capability targets for policies, incentivisation schemes, and regulatory frameworks to be put in place at national and regional levels.

[Perform scenario analyses on decarbonisation pathways](#)

This is a combination of the maturity assessment and the latest and projected (if available) traffic volumes. Using a three-layer system (do-nothing, reaction to threats, proactive

prevention), it will be possible to evaluate the urgency levels in each country or route in terms of emissions. It is important to internalise direct and indirect emissions associated with rail freight operations to fully understand the long-term costs of carbon emissions so that investments can be appraised appropriately. This will support the prioritisation of projects and the definition of policies to facilitate the decarbonisation pathways in ESCAP countries.

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