MEASURING RAILWAY INFRASTRUCTURE CARBON:

A ‘critical’ in transport’s journey to net-zero

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Contents

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The work has been conducted with Transport for the North (TfN) as a research partner and is contributing to their commitment to better integrate embodied emissions into recommendations on policy and infrastructure investment. However, the findings and policy implications are those of the research team and should not be seen to be endorsed by TfN. We would like to thank Network Rail for their support in data collection.

This report is the responsibility of the authors and does not imply endorsement by the funders. Any errors or emissions are those of the authors.

Further information

This technical report sits alongside a report on road infrastructure carbon and a policy briefing. All three documents can be found at: https://DecarboN8.org.uk/EmbodiedEmissions

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Glossary

Capital carbon	The embodied carbon plus the emissions from external sources, including material and energy, used by mobile plant and equipment, site utilities, personnel transport to site etc
CCS setting	An optimistic setting used in the sensitivity analysis of this study where the negative carbon derived from negative carbon technology (mainly BECCS and DACCS) is made accessible to quantify/test the maximum possible decarbonisation of infrastructure that could be achieved
Consumer Transformation pathway	Scenario from FES2020, the second fastest route to decarbonisation where there are significant societal changes, higher levels of energy efficiency, and lower levels of energy demand.
Cut-off criteria	Used in the system boundary to highlight materials or any particular stages that may be excluded from the analysis.
Embodied carbon	The carbon dioxide emissions associated with the construction materials and the construction of an asset or a piece of infrastructure, across its whole life cycle
Embodied energy	The energy consumption (*in joules*) associated with the construction materials and the construction of an asset or a piece of infrastructure, across its whole life cycle
FES2020	Future Energy Scenarios 2020, a report published by the UK National Grid in July 2020
Functional unit (F.U.)	A quantified description of a product and/or its functionality, which in comparative LCA, creates a level-playing field (a standard unit) for the comparison of environmental performance of two or more products
GWh	Gigawatt hour
ICE	Inventory of Carbon and Energy (ICE)
kWp	Kilowatt peak

Leading the Way pathway	Scenario from FES2020, the fastest route to decarbonisation where both the supply and the demand side show significant positive changes, functioning at the highest possible efficiency
Life cycle assessment (LCA)	A systematic methodology developed and applied to assess the environmental impact associated with a selection or all of the life cycle stages of any given asset or an infrastructure
MTC	Megatonnes of carbon dioxide
No CCS setting	A setting used in the sensitivity analysis of this study where the negative carbon derived from negative carbon technology, mainly BECCS and DACCS, is not accessible for the decarbonisation of the transport infrastructure, and rather reserved for ‘hard-to-decarbonise’ sectors (mainly aviation and agriculture)
OLE	Overhead Line Equipment are the overhead assembly of catenaries and support structures that supplies electricity to the train’s engine through its receiving components
Operational carbon	The carbon dioxide emissions associated with the operation and maintenance of a built asset, across its whole life cycle
Steady Progression pathway	Scenario from FES2020, the slowest route to energy grid decarbonisation
Sub-system	A sub-system corresponds to each of the life cycle stages across the whole life of a built asset or infrastructure
System boundary	Used in LCA to define which unit processes or life cycle stages are included and excluded when assessing the environmental performance of a built asset or infrastructure
System Transformation pathway	Scenario from FES2020, the third fastest route to decarbonisation where the initiative lies with the integration of innovation at the supply side
TCO2eq	Tonnes of carbon dioxide equivalent
TWh	Terawatt hour

Executive Summary

The Department for Transport's Decarbonisation Plan focuses on 'tailpipe emissions' from vehicles. Whilst the plan acknowledges embodied emissions in the construction and management of infrastructure and the construction of rolling stock, no clear indications of the scale of these emissions nor their significance have been provided. The national accounting responsibility for those embodied emissions sits with the Department for Business, Energy and Industrial Strategy (BEIS). So, the department responsible for generating these emissions through decisions to expand infrastructure (DfT) is not responsible for managing those emissions. The reality for organisations such as Transport for the North (TfN) or Network Rail, promoting new infrastructure, is that they will need to present a 'whole-life' approach which deals with all the carbon implications of their choices.

Shifting to a 'whole life' carbon (WLC) approach requires an understanding and assessment of embodied carbon at the 'design' stage to become a part of strategic decision making, leading to investment programmes compatible with climate commitments. However, perhaps because of the lack of focus on these issues within DfT and the lack of responsibility for transport infrastructure within BEIS, there remains limited guidance, expertise and experience in understanding how important embodied emissions might be to different types of investment cases.

The aim of this work is to quantify the embodied and operational carbon associated with the systems and sub-systems in rail based transport infrastructure to inform decision making. Some of the key findings of this analysis and general conclusions have been presented here.

Summary of Main Findings

- The whole life carbon (WLC) impacts of some planned developments/upgrades in the rail transport infrastructure (new tracks, bridges overhead line equipment (OLE) and station upgrades) were estimated employing life cycle assessment, over an assumed service life of 60 years.
    - The whole life carbon of 1 km of track, modelled within the boundary constructs and the assumptions adopted in this study, is determined to be 2,024.3 tCO_2eq for ballasted track and 1,662.2 tCO_2eq for ballastless track.
    - The whole life carbon (WLC) per unit of ballastless track is relatively low (-20%), while the overall energy intensity was observed to be about 2% higher, compared to that of the ballasted tracks.
    - Resistance to vibrational impacts and lack of other moving parts means ballastless track needs little to no maintenance over the 60-year service life, saving 50% of operational emissions, relative to ballasted tracks.

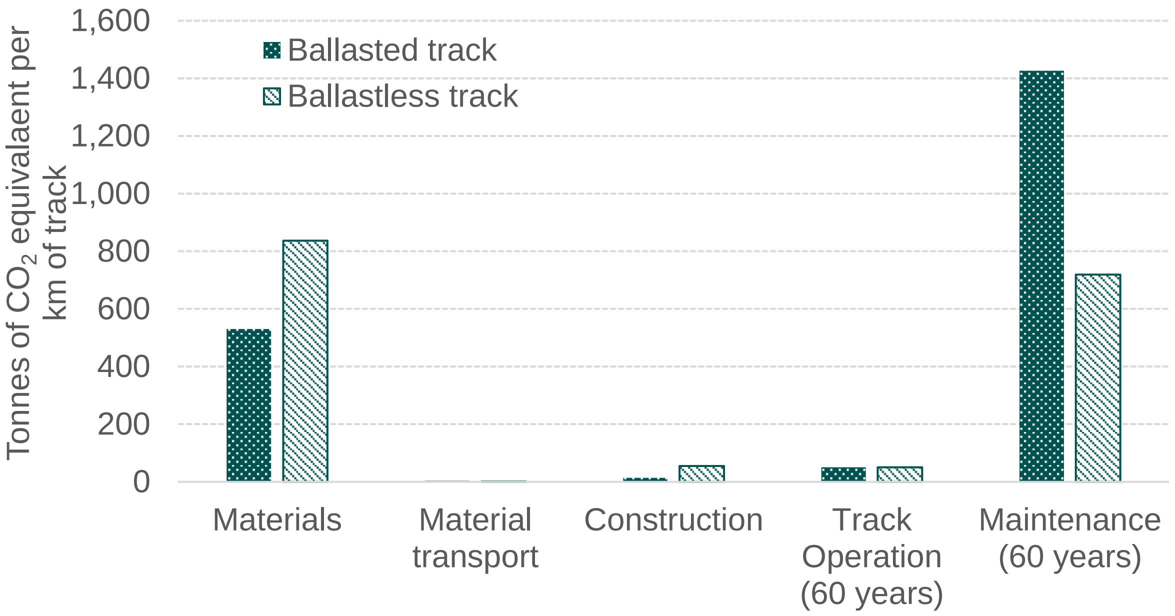

Figure 1: Embodied and operational carbon of 1 km of ballasted and ballastless tracks

- Track maintenance is the most material and energy intensive phase in the life cycle of a rail track, contributing 70% of the track's whole life carbon.
- The main embodied carbon contributor for the tracks is the steel in the rails, clips and the rebar in the sleepers (58% of the embodied carbon of 1km track).
- OLE operation and maintenance are the most carbon intense phases and are responsible for 85% of its whole life carbon (electrified single track – 1,696 tCO_2eq).
- The main embodied carbon contributor here again is the steel foundation (92% of the whole life carbon), followed by the conductor materials used in the catenaries of the OLE.
- Generally, carbon emissions related to energy demand peak during the 'track operation and its maintenance' over its life-period (2.8 GWh over 60 years).

Sensitivities to intersectoral interactions

- Use of low-carbon alternatives to the sleepers in new-rail-tracks reduces the whole life carbon by about 6-15% over the asset's life period of 60 years.
- There is potential to extend these savings to 20-35% by integrating more recycled steel into the rails and for reinforcing concrete structures that are required to be replaced every 15-20 years.
- This study adopts two of the four grid decarbonisation pathways (Steady Progression and System Transformation) published by the National Grid in their 'Future Energy Scenarios 2020' report.
- A steadily decarbonising energy grid delivers whole life carbon savings for 1 km of an electrified rail track by about 12-23% under the 'Steady Progression' pathway, which is elevated to 25-64.5% under the 'System Transformation' pathway, relative to baseline figures estimated for the year 2020.

- The study assessed the use of solar PV modules of varying capacities (23-96 kWp) in stations of specific passenger capacity, over a service life of 60 years in the context of a steadily decarbonising grid.
    - Carbon savings from the use of solar PV modules, that displaced grid-electricity, steadily decrease with time against the backdrop of a decarbonising grid.
    - The solar PV modules are capable of paying-off their embodied carbon within one to two years of their installation (depending on the capacity installed and energy efficiency) and can therefore act as further mitigation against the embodied emissions from construction and maintenance. For some schemes this can be very significant although it is highly context specific.
    - It is also possible that the carbon benefits of such installations are accounted for in the grid decarbonisation assumptions made in the FES study. Further investigation is required to explore whether PV can be used as further mitigation to carbon emissions from construction and maintenance.
- Even in a hypothetical scenario, where an optimistic grid decarbonisation (System Transformation) pathway is applied across the whole life of the built assets (1 km of a new electrified single-track), with access to negative carbon (‘CCS’ setting), there is a 22-48% WLC impact that is ‘hard-to-decarbonise’, posing a gap in achieving carbon neutrality past the net-zero year (2050).
- One of the main contributors to this ‘stubborn’ remainder of whole life carbon is the embodied carbon in the materials.

RAIL INFRASTRUCTURE CARBON ASSESSMENT

1 Rail infrastructure – an introduction

The sixth carbon budget, published by the Committee on Climate Change in 2020, addresses the need for the reduction of tailpipe emissions from road transport. It also mentions ‘behavioural change to shift journeys onto low-carbon modes’ as a critical measure for transport carbon reduction (Committee on Climate Change, 2020).

Rail is 79-85% more carbon efficient compared to other modes of transportation, especially car and domestic air travel, and has further benefitted from the highest level of electrification to date, compared to any other means of surface transport (Department for Business, Energy and Industrial Strategy, 2021a).

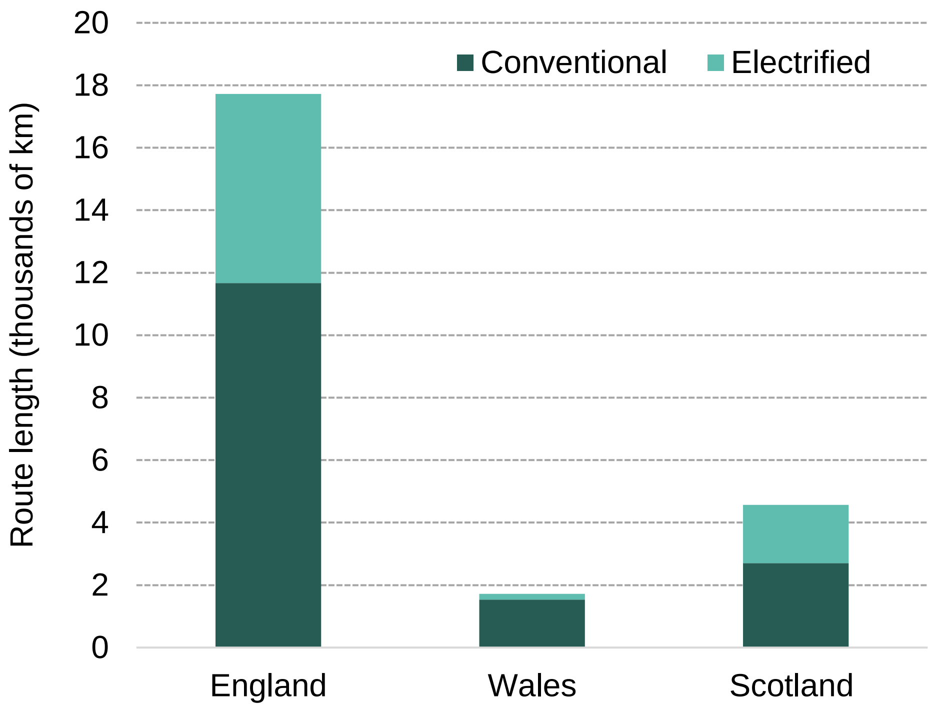

Figure 1: Total length of rail-route in the UK (Source: Office of Rail and Road, 2020)

In 2019, the Rail Industry Decarbonisation Taskforce published pathways to decarbonise rail by implementing policies and targets which include a phase out of diesel traction systems and other key delivery plans as part of the electrification expansion (Rail Transport Decarbonisation Taskforce, 2019). With electrification expected to dominate rail traction systems soon, a steadily decarbonising energy grid would greatly support the mitigation of its operational carbon. However, the capital carbon from the design, construction and maintenance of the assets resulting from the infrastructure expansion and electrification is currently hard-to-mitigate. If overlooked, this may lead to poorly phased work programmes which do not make best use of technological advances and a decarbonising grid.

1.1 Methodology

Network Rail (NR), in its guidance, has set a minimum requirement of capital carbon assessment for any development scheme that falls within a specific technical and economic budget threshold of £1m and above (Network Rail, 2021a). Within this guidance, there is clear evidence of an understanding of the linear relationship between carbon efficiency and costs, through material efficiency. To ensure adherence to the principles of Publicly Available Guidance PAS 2080:2016 – Carbon Management in Infrastructure, NR recommends the use of RSSB Rail Carbon Tool[1] to undertake capital carbon assessment for development schemes. As recommended within this guidance, embodied carbon associated with the 'bill of materials' including the aggregates, steel or rail and sleepers, concrete, and insulation materials, will all be estimated via the RSSB Rail carbon tool. The embodied and operational carbon emissions are estimated using the following standard approach employed in life cycle assessment:

$$\textbf{GHG emission (tCO}_2\textbf{eq) = material and energy flow} \times \textbf{emission factors}$$

Where material flow is generally measured in *kg* per functional unit and the energy flow is measured in *litres* for liquid fuels, m^3 for gas, and *kWh* for electricity consumed. The emission factors used in estimating the carbon emissions are from Inventory of Carbon and Energy (ICE) v2 that are built into the RSSB Rail Carbon Tool.

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[1] RSSB Rail Carbon Tool is a web-based free to access tool to model, analyse, compare and report carbon footprint associated with a project or activity, supporting the stakeholders of the UK rail industry (RSSB, 2021)

2 Scope and functional unit

The study aims to quantify the infrastructure carbon (embodied and operational carbon) attributed to the life cycle stages of the key components of the rail-infrastructure (for example: rail track, electrification structures, bridges, stations, etc). It is customary within environmental impact assessment methods (including LCA) to set a functional unit that establishes a level playing field for two or more functionally comparable candidates. The functional unit set for this study is 1km of a single track. This study also evaluates the rail carbon's sensitivity to innovations that are presently piloted in the existing rail network and the influence of a steadily decarbonising energy grid; taking into account that the rail sector has been promised an efficient and cost-effective electrification, coupled with battery-operated traction systems, by 2050 (Rail Transport Decarbonisation Taskforce, 2019).

The carbon estimates from this analysis will provide an indicative benchmark, offering comparability in terms of variations in the technical applications, and a potential methodology for future scheme appraisal integrating whole life carbon impacts. The scope for whole life carbon encompasses the stages (or sub-systems) involving acquisition of materials for the construction of these components, their transportation to site, construction, operation, and maintenance of the assets. The 'operation' sub-system here corresponds to track operation involving operation of switches and crossings (S&Cs), power system operations (particularly OLEs) and signalling systems. In contemporary LCA, the products (or assets) tend to reach their end of functional life, whereby they may be decommissioned, involving route closure and salvaging of materials for reuse. However, unlike other products, most rail tracks tend to remain operational with routine maintenance and a 'decommissioning' phase seldom occurs. As a result, this phase has been excluded. A brief schematic of the system boundary explained earlier has been presented in Figure 2. It is crucial to note that whole life carbon analysis would only account for direct emissions from the construction, operation and maintenance of the assets, excluding vehicular emissions (from rolling stock) that arise from consumption by users (user-emissions).

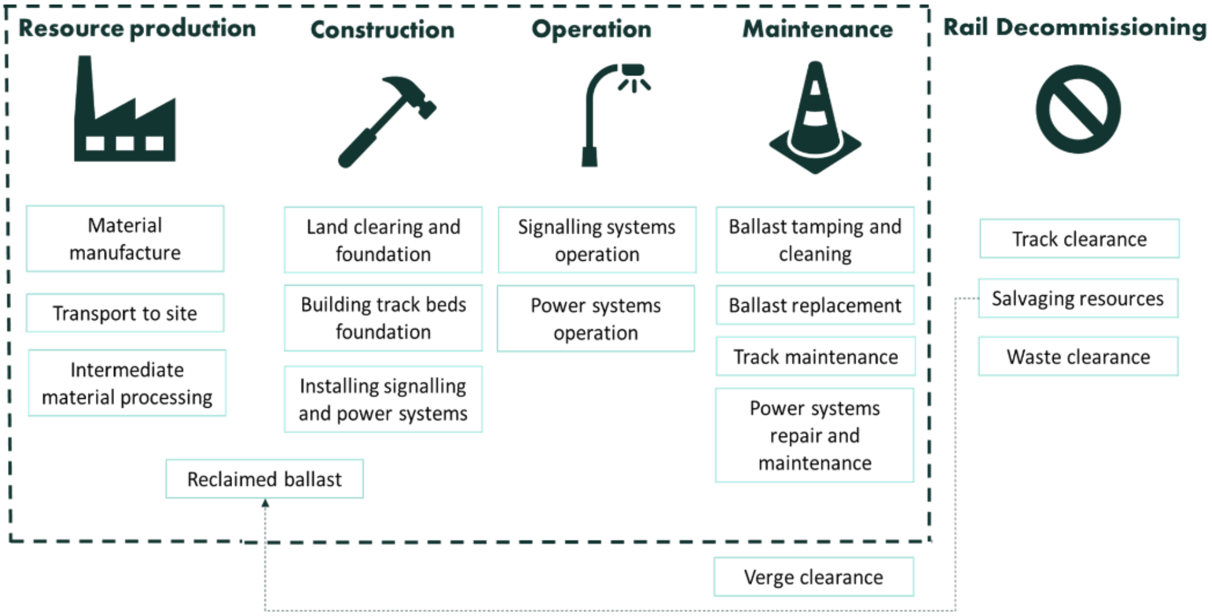

Figure 2: A breakdown of the processes and sub-systems embedded in a rail-track, representing the system boundary of this study

Owing to the diversity of rail components that will be assessed as a part of this analysis (ancillaries and structural components), the carbon impacts will be estimated per unit components, unlike tracks (where we fix the functional unit as 1 km). Details on the functional units used for each of these components have been provided under their respective sections.

2.1 Inventory analysis

Rail infrastructure is complex in nature but is generally made up of some of the key components listed below:

- Station construction – train control system, escalators, lighting systems for either passenger stations or freight terminals
- Train construction for passenger or freight transport
- Rail track foundation
- Track construction – including electrical control, power and lighting (if necessary) systems
- Tunnel and bridge construction

There are several studies that look into all or parts of the infrastructure (Stripple and Uppenberg, 2010; International Union of Railways, 2016; Kiani et al, 2008; Du, G, 2012). The aim of this study, however, is to quantify the embodied carbon encompassing material and energy flow through the construction, operation and maintenance of the railway tracks. The type of track construction adopted in this study will be suited to accommodate its potential conversion to high-speed rail (250km/h). It is crucial to acknowledge that, while ballast track bed is the traditional option for rail tracks, there are other types of track bed construction (eg slab track). Each construction, with benefits and issues concerning their mechanical and environmental performance, could provide a unique perspective accounting for innovations in commercial rail technology. Slab tracks have been employed in the twin-bore tunnel sections of HS2 route, specifically for their long-term environmental benefits and to reduce vibrational impacts (Temple-ERM, 2013). Therefore, the whole life carbon analysis will focus on both ballasted and ballastless track beds. There are five ballastless track types which include embedded rail, resilient baseplate, booted sleeper, cast-in sleeper and floating slabs (Britpave.org,uk, 2021). For this high-level analysis, we will be considering the material and design specifications for embedded rail. Some of the common components of both types of track types include the following:

1. Sub-grade – base layer
2. Geotextile layer (for drainage)
3. Sub-ballast / concrete layer also called Sub-base
4. Ballast or in-situ concrete pavement (depending on ballasted or ballastless track type)
5. Reinforced concrete sleepers forming the tracks for both ballast and slab tracks
6. Steel tracks locked in place, onto the sleepers

The track foundation is fairly similar in composition for both types of track bed construction and it has been discussed in detail in earlier published literature (Kiani et al., 2008; Hill et al., 2012; Stripple, 2001). Therefore, this study lays further emphasis on points 4 to 6 above which jointly make up the different types of track beds discussed below.

Track beds

Ballast track beds

This is the most commonly built track bed, comprising a sub-ballast and ballast layer on top of a well-built sub-grade layer. The ballast is made of high-quality uniformly sized aggregates that can provide sufficiently strong bed/base for the precast concrete sleepers and the steel tracks. Ballasted track laid below the sleepers about 30-50 cm deep offers better drainage performance and flexibility for repairs over the life of the rail-tracks (RailUK, 2020), compared to ballastless tracks. However, during operation, the ballast tracks tend to get compacted or worn-down from subsequent grinding, affecting the structural integrity long-term. As a result, a ballast requires routine maintenance via tamping (one to two years), cleaning (every 10 years) and replacement (every 20 years). The concrete sleepers require replacement every 20 years.

Slab track beds

Slab track is a form of ballastless rail track bed, a concrete intensive alternative to ballasted beds, which offers better load transference and stability unaffected by high-velocity rail, heavy rail, and tram systems. In this case, the ballast layer of the track is replaced by a concrete bed on top of another layer of concrete sub-base. The rigid construction design of the different track components means there is far less chance for aggregate grinding beneath the tracks and therefore, it is better for operational air quality. Fewer moving parts also means more durability and a longer service life over the period of its functional life (50-60 yrs). However, this type of construction is concrete intensive, with a significant environmental burden. This type of construction may not be suited to certain types of soil, such as soft dirt road, clayey soil, etc. Therefore, the sub-grade layer must be adjusted using an appropriate mix of earth materials to provide a stable foundation for the upper layers. For this analysis, standard dimensions and specifications that are recommended within the RSSB rail carbon tool have been adopted. With both these constructions, the steel tracks are fastened to the steel reinforced, rigid, pre-cast concrete sleepers, lined with insulating rubber pads.

Maintenance and renewal

The maintenance routine assumed for ballasted track is an industry standard. Heavy loads from rail traffic tend to deteriorate the track bed. Therefore, the ballasts are regularly compacted via tamping, restoring the correct position of the track on an annual basis. The ballast is required to be regularly cleaned due to ‘fouling’ and upon reaching a ‘fouling limit’, the ballast is replaced (Network Rail, 2021b). New ballast is, however, assumed to be added as per the industry practice during the tamping (5% by weight) and cleaning (30% by weight) to cater for the losses from grinding and compaction (Kiani et al., 2008). The original ballast tends to be discarded at the renewal stage altogether, as they are usually too contaminated to be downcycled or repurposed for other projects. The other sub-components of the track, such as sleepers and the steel rail are subject to a detailed technical inspection, which informs the decisions for maintenance renewals. The steel sleepers and rails that are replaced are usually recycled at 97% efficiency for reuse alongside virgin steel in the UK (Network Rail, 2021b). The fastening clips and pads are assumed to be replaced completely. The clips are assumed to be recycled at 85% efficiency (Kiani et al., 2008), whereas used insulator pads are usually disposed of.

As for the slab tracks, the in-situ concrete tracks are assumed to have a longer life span compared to the conventional ballasted tracks (>60 years). However, the rail is assumed to be renewed on the same schedule as for conventional tracks. Further details on the materials requirement for maintenance of rail tracks and frequency of part replacement has been provided in Table 1.

Phases	Parameters	Sub-parameters	Quantity	Units
Rail bed and track materials	Ballasted track	Sub-base aggregates	3,000	tonnes
		Pre-cast concrete sleepers – G44	1540	each
		Ballast	4,200	tonnes
	Slab (ballastless) track	Sub-base aggregates	2,000	tonnes
		Sub-base cement	125	tonnes
		In situ concrete pavement	1,314	tonnes
		Pre-cast concrete sleepers – G44	1540	each
	Other common components	Fastening	6,160	each
		Rail pads	6,160	each
		Steel rails	121	tonnes
Overhead Line Electrification (OLE)	Structure	Cantilever assembly	20	each
		Steel Mast base	20	each
		Steel pile foundation	20	each
		Droppers	100	each
		Contact wires	1000	metres
		Aerial earth wires	1000	metres
		Catenary wires	1000	metres
Switches and Crossings (S&Cs)	Structures	S&C unit	1	each
Bridge	20m span	Concrete	52	tonnes
		Steel	134.4	tonnes
Machinery *(mainly fuel consumption)*	Construction	Sleeper paving	70	litres
		Rail laying	185	litres
		Ballast spreader	120	litres
		Ballast tamper	480	litres
	Maintenance	Ballast cleaner	255	litres
		Ballast changing	255	litres
		Concrete paver	185	litres
		Rail laying	185	litres
		In-situ slab former	220	litres
Operation and Use	Points, S&C operation	Electricity	50.4	MWh
	OLE		47	MWh
Maintenance *(frequency)*	Ballasted tracks	Tamping	Annually	
		Cleaning	10	years
		Ballast replacement	30	years
		Concrete sleepers	30	years
		Rail renewal	20	years
	Ballastless tracks	Concrete slab tracks	>60	years
		Rail renewal	20	years

Table 1: 'Bill of materials' and other specifications for the construction, operation and maintenance of 1 km rail track over a service period of 60 years

Ancillaries

Switches and Crossing

Switches and crossings (S&Cs) form one of the most fundamental structures of the rail network and serve a purpose connecting nodes between different rail tracks/rail lines. Network Rail operates just over 21,000 S&Cs in Britain's rail network. S&Cs are ideally 67.5 m long per unit (Coleman and Cornish, 2010). Some of the key components of an S&C include switch rails, crossings, outside rails, and breather switches. Installed as a pre-assembled unit, S&Cs tend to face significant stress and wear from continuous traction, and therefore, their safety issues are paramount within track maintenance. Being steel-intensive, the performance and mechanical characteristics are evaluated on a regular basis and with regards to the industry standard. We have assumed the maintenance of these components similar to that of the rails (every 10-15 years).

Overhead Line Equipment (OLEs)

OLEs are now a standard technology adopted for current and future rail electrification schemes, currently making 25-30% out of the 38% (6,048 route km) of all electrified routes in the UK. OLE is an overhead assembly of catenaries and support structures that supplies electricity to the train's engine through its receiving components. Currently, electricity supply from the national grid (400 kV) is fed to the OLE equipment via feeder sub-stations (25 kV) that are placed at regular intervals (every 60 km) and supplemented by a booster transformer (every 3-8 km). A new system employs auto-transformers that eliminate the need for both the recurring booster transformers and thus the feeder sub-stations. For further details on the technical specifications, please see Network Rail (2015). The new system for overhead line equipment (OLEs) is currently adopted for installation across the UK to accommodate interoperability of trains and for the ease of technological retrofit. Though there have been variations in the implementation of electrification on the British rail network since its inception in the 19th century, the current and future standards for electrification are the 25 kV AC overhead systems. Hence, this study has adopted the 25 kV AC overhead as a default electrification system for both benchmarking and future scheme development in the upcoming case-studies.

For brevity, the study will emphasise only the material requirements for the OLE foundation, catenaries, their installation, and the assembly. The standard components of an OLE include the contact wires that are required to be installed with sufficient tensioning between the 'contact' and the support structures for uninterrupted power supply, even under adverse weather conditions. The contact wires are solid copper wires that are usually 107 mm^2 thick. The contact wires are suspended from the vertical copper cables called droppers at regular intervals (5 cables every 50 m). The droppers are supported by the catenaries that are solid copper bronze wires (65.8 mm^2 thick). These wires are held overhead by masts supported by 5 m steel pile foundations. Due to the high-level nature of this analysis, we have chosen to exclude finer data on fixings, brackets, bolts etc. The masts are assumed to be installed at 50 m interval for 1 km (Network Rail, 2021c). The Bill of Materials has been adapted appropriately for single-track electrification, based on the data acquired from Network Rail, for both the benchmark and for our case study. Primary data (component replacements and affiliated material requirements) for the maintenance of OLE is currently unavailable, however, data from open scientific literature has been adopted for energy consumed over OLE maintenance over a temporal boundary of 60 years (Hill et al., 2012).
The energy demand of the OLE equipment is dependent on the rail-route traffic: the technical characteristics of the rolling stock and the passenger capacity supported by the network accessing these lines. However, considering the electricity supply to the transformers and the supporting

structures falls within the scope of the infrastructure, the resulting emissions from energy supply is treated as operational emissions. Thus, operational emissions resulting from the electricity supply to the supporting OLE structures, though autotransformers, over a 60-year life-period (1,800 hours per year) have been accounted for within the infrastructure carbon estimation. The sensitivity of this operational carbon to a rapidly decarbonising electricity grid has been evaluated in the upcoming sections.

Structural components

New station and platform extensions

Stations vary by capacity from simple two-platform two-track structures, to complex structures with multiple platforms, multiple track structures, additionally equipped with commercial retail spaces. Construction materials and other equipment primarily consumed for station construction include concrete, bricks and steel for furniture, access facilities such as ramps, elevators, escalators and flooring. Material requirements are, however, highly variable with the planned scale of expansion (intended platform length), existing passenger capacity etc. Station operations that are mainly energy- and hence carbon-intensive include heating, lighting, signalling, communication, and track operation. These parameters are recurring, and from a whole life carbon viewpoint, are significant sources of long-term operational carbon. Hence, the sensitivity of these parameters to accessible commercial low-carbon energy technologies (such as monocrystalline solar PV energy systems) has been undertaken in the upcoming sections.

To account for the operational emissions of a station that is powered by electricity (in the baseline scenario), stations of varying passenger capacity have been assumed in this study. Station passenger patronage can range anywhere from 100 thousand to 3.3 million passengers per year, and the energy demand for the operation and maintenance of these stations is variable and yet perceivably high over the temporal boundary of this study (60 years). In this study, a station’s energy demand is estimated to establish a baseline operational carbon threshold, at an average of 0.045 kWh/passenger per year, factoring the plausible patronage ranges of 300 thousand, 600 thousand, and 3.3 million. Data on energy consumption per passenger was acquired from the review, analysis of relevant data from earlier published reports and literature (Eerenbeemt, 2021; Hill et al., 2012; Merchan et al., 2020). This figure was then adjusted to the growing trends in passenger rail usage, applying improvement in overall efficiency in energy consumption (Department for Business, Energy and Industrial Strategy, 2021b; Office of Rail and Road, 2021). The materials required for the platform/station extensions are modelled, analysed, and discussed in section 0.

The RSSB Rail Carbon Tool contains a database of past projects, the models of which could be adapted or new models could be developed. For this analysis, materials required for benchmark construction of a new platform were adapted from that of the past projects and modelled within the constructs of this study’s boundaries. Material and energy consumption have been adapted and modelled for installation of a new platform that is 350 m long per track. This assumption is drawn from the spatial observation of the stations that are to be assessed as case studies within this report. Unlike the tracks, the whole life carbon, for platform extension, is estimated for a station with two adjacent platforms that are 350 m long.

Bridges

For bridge constructions, a commonly used single-track half-through bridge otherwise called a ‘standard U-bridge’, which is 20 m long, is assumed. Key components of this bridge include concrete beam deck, cill beams and parapets. Scheme developments planned for some of the case studies include replacement of road crossings with overbridges. Finer details regarding the construction designs or lighting are not available. Hence details regarding track service, drainage, bearings and abutment have been excluded from this analysis. There is little to no information on the procurement specifications or locations of the primary final suppliers that cater to the material demands of capital projects. This study assumed 50-100 km, depending on the material supplied for the benchmark work, while variations in these transportation distances are adopted for the case studies based on their strategic procurement locations within the Northumberland region (Network rail, 2021).

General Considerations and Limitations

For embodied emissions to influence and shape a strategic portfolio it is necessary to estimate emissions at a stage where only an approximate idea of route alignment is known. The actual alignment, numbers of bridges or tunnel sections could all impact on the actual figures. However, our aim is to provide some reasonable approximations that enable this to be deployed. Here are the list of assumptions that have been adopted into the general analysis and reporting of results in the upcoming sections:

- This study is mainly exploratory in nature, attempting to gauge the significance of embodied carbon within ‘infrastructure’ emissions. As a result, the nature and the type of rail infrastructure components assumed for both benchmarking and application in the case studies are speculative in nature.
- The ‘bill of materials’ adopted here for the rail transport infrastructure construction are restricted to the current scenarios and design specifications and are restricted to England only.
- The low-carbon and secondary alternatives adopted for this study include a mix of candidates that are either planned for or currently piloted within the existing rail routes.
- Assumptions adopted for the sensitivity study involving a steadily decarbonising energy grid are restricted to the national net-zero strategies and goals in the UK. Net-zero strategies that are related to construction sector (for application to the rail’s LCA) have been excluded due to lack of data on adaptable or applicable pathways within the scope of this study.
- FES2020 provides carbon intensity for a steadily decarbonising grid between 2020 and 2050. To keep uncertainties associated with any future estimates to a minimum, grid carbon intensity has been extrapolated only between 2050 and 2060. Therefore, the sensitivity study concerning a decarbonising grid has been undertaken only between 2020 and 2060 (40-year service life).
- There is little to no information on the material procurement specifications and sources. This study has, therefore, made assumption on the distance between storage/supply deports and the construction sites.

- Emphasising mainly the embodied and operational carbon, details related to workforce transit, site-level energy and associated material consumption (stationery, site utilities etc) are excluded from the scope of this study.
- The end-of-life management of the residual materials from the construction phase and those that are generated over the operation and maintenance of built assets, and potential circularisation of resources that may offset the whole life carbon have been excluded due to lack of primary data. Informed assumptions on material circularity based on the evidence available from published industrial and scientific literature have been adopted for the sensitivity study.

The discussion of the assumptions made in this study should form an important part of the development of a method which can be adopted for early-stage strategic assessment.

2.2 Sensitivity study

Integration of Sustainable alternatives

Integrating sustainability into infrastructure expansion is in the interest of rail transport stakeholders owing to both the associated cost and the carbon savings (Network Rail, 2021a). From the viewpoint of sustainable construction, incorporation of recycled or reclaimed components, particularly sleepers, have been trialled along a number of routes in England (Network Rail, 2018a, 2021b, 2021d; Rempelos et al., 2020). The goal of this sensitivity analysis is to evaluate the influence of these ‘sustainable’ alternatives to conventional wood and concrete sleepers on the whole-life carbon impacts of the rail-tracks. They have been analysed in greater detail below.

RE Scenario_1: Recycled composite sleepers

Railway sleepers are crucial to the quality of a rail track’s functionality. The purpose of the sleepers is to transfer the load from the vehicles to the ballast while holding the rails in place. Most of the traditional wooden sleepers have now been replaced by concrete sleepers, the elemental components of which are broken down for downcycling, and used for track bed construction elsewhere. Nevertheless, the environmental burden of concrete has led sustainability engineers to pursue greener alternative composite sleepers.

Here, a low-carbon and resource efficient alternative to conventional concrete sleepers is discussed where a concrete inner core (made from conventional Portland cement) is covered by an outer shell made from powdered rubber and recycled plastic blend. The powdered rubber is a secondary resource sourced from disposed tyres and recycled plastic or polyolefins, from the waste streams of the packaging sector. The outer shell protects the concrete core from abrasive damage (upon interaction with the ballast) and boosts the sleeper’s service life by 30-60%, significantly reducing the frequency for sleeper replacement (current service life 35 years). The tyre rubber is granulated and treated prior to its conversion for use in this innovative low-impact sleeper. A paper by Dolci et al. (2020) provides a detailed account of the mechanical characteristics and relevant details on the life-time performance based on the sleeper-ballast interaction. Within this study, the overall life cycle impact of these innovative, commercially available sleepers was undertaken with a well-defined system boundary, and the scope of analysis also included the end-of-life reclamation of these disposed rubber tyres. Similarly, the end-of-life routes for processing plastic wastes in the plastic recycling facility and the node at which these components (powdered reclaimed tyre rubber and the recycled polyolefin mix) are combined to create the material suited for injection moulding of the outer shell of the sleeper, have also been detailed.

The exact composition of the composite sleepers remains undisclosed by the authors due to intellectual property concerns (Dolci et al., 2020). However, from the review of related literature on products of similar specifications and the acceptable stiffness, strength and failure behaviour reviewed by other studies, the material composition of the outer shell (made of a blend of powdered rubber and recycled polyolefins) is assumed to make up 20% of the weight of the sleeper itself (Ferdous et al., 2015a; Network Rail, 2021d; Salih et al., 2021; Yu et al., 2021). Further details on the composition of this sleeper can be found in the Appendix.

RE Scenario_2: Synthetic Fibre-reinforced Foamed Urethane (FFU) sleeper

Developed and implemented by the Japanese National Railways in the 1970s, FFU sleepers are viewed as valuable alternatives to the wooden and concrete sleepers. Showcasing significant resistance to environmental burdens such as moisture, heat and corrosive action, and resistance to cracking, stemming from their comparable elasticity, FFU sleepers are also less prone to mechanical failures or disintegration over their expected service life, compared to the traditional candidates (Ferdous et al., 2021, 2015b; Koller, 2015; Sengsri et al., 2020). These synthetic sleepers have also been promoted to provide a service life of about 50 years, based on the inspection of the 30 years old, currently functional FFU sleepers (Ferdous et al., 2021; Sekisui Railway Technology, 2021).

FFU synthetic wood sleepers are manufactured by drawing oriented glass-fibre strands through a pulling device. This is called pultrusion. The pultruded strands are compressed and coated in polyurethane, following a curing process at high temperatures, leading to a pore-free product comparable in performance to the conventional candidates (Koller, 2015). The production process, however, is energy intense thus rendering a high embodied energy content (roughly 6.7 GJ per sleeper), compared to concrete (1.9 GJ per sleeper) (Kaewunruen and Liao, 2021). This is likely to incur a significant impact on the embodied carbon over the life cycle of the asset in question. However, the 150% longer service life of the sleeper means reduced frequency of sleeper replacements. The trade-offs in the capital and operational carbon are evaluated and reported further in this study. Further information on the technical product characteristics and embodied carbon evaluations can be found in openly available literature (Ferdous et al., 2015b; Kaewunruen and Liao, 2021; Koller, 2015) and in the Appendix. Alternative solutions to the glass-fibre filling of these sleepers have been identified in the open literature, including natural fibres such as coir, grass and food sector by-products like olive kernels (Kuranchie et al., 2021, 2021; Ferdous et al., 2021). However, in this study, we restrict the analysis of alternatives to products that are either currently used or piloted in the rail infrastructure and those that are commercially accessible.

RE Scenario_3: Recycled steel in steel sleepers

An additional scenario where the steel sleepers are assumed to contain 30% of recycled content (similar to that reported by (Rempelos et al., 2020) practiced in parts of the UK rail industry) has been assumed as a replacement 100% virgin steel sleepers.

Installation of Solar PV systems

Use of solar PV energy systems is catching up to become one of the most ideal sustainable solutions for energy efficiency in the rail infrastructure (Network Rail, 2018b). In 2018, station upgrades to King's Cross and Blackfriars stations in London, included significant resource-efficiency improvements such as the use of secondary material blends, rainwater harvesting, and the installation of thousands of square metres of solar roof panels. For our sensitivity study, we have hypothesized similar rooftop installations as a part of the station upgrades, and potentially for platform extensions of different scales, drawing from the location and orientation of the spaces suitable for solar panel installations. This has been undertaken for hypothetical purposes, and therefore, ideal geometric, inclination and location specifications have been assumed. In this study, PV capacities of 500 m^2, 330 m^2 and 120 m^2 were assumed, drawing from the space available on the station roof and the potential rooftop capacity that could be added by the extended platforms in the locations of our case studies. These assumptions have been made using commercial capacity estimation tools that are available on specific guidance websites (Circular Ecology UK, 2021; GeoGreenPower.co.uk, 2021). In 2021, solar panels in the UK were capable of generating energy at an efficiency of 15-22%, depending on the location, orientation, weather conditions, age of the panels etc (Greenmatch, 2020). At an efficiency of 15%, 1 m^2 of a monocrystalline solar module would produce 150 watts. Based on an update publication on solar PV energy systems installation by Network Rail, the power output of south-facing solar PV units, installed in the North of England, is estimated to produce 0.304 kWp (kilowatt peak) per m^2 of the installed solar module (Network Rail, 2019).

The embodied carbon of the solar module (material requirements for a monocrystalline PV module) have been found to vary significantly, ranging from 2,500 to 2,635 $kgCO_2eq/kWh$, in published literature (Circular Ecology UK, 2021; Finnegan et al., 2018; Hammond et al., 2012; Louwen et al., 2016; Pehl et al., 2017). Based on the existing data, the embodied carbon of the materials used in the production of monocrystalline PV modules, extrapolated to present day, which include connector sections and the output assembly, supporting the operation of 1 m^2 panel, is estimated to be 0.118 tCO_2eq. The operational carbon associated with the solar PV systems depends on the capacity installed per train station, which in turn is dependent on space availability, panel orientation, location etc. While fulfilling wholly or partially the energy demand of the station and platform, the solar modules are assumed to deliver excess energy back to the grid. This amount of grid-electricity saved by the asset is accounted into the operational carbon estimation, as 'avoided carbon' (calculated as tCO_2eq over a 60-year period). The calculated 'avoided carbon' also factors into the carbon intensity of displaced grid-electricity over this 60-year period. Therefore, the carbon savings acquired from solar installation gradually drops with a steadily decarbonising grid. Despite this, generation and supply of solar energy to the grid has been suggested as an indispensable step in transport electrification (Committee on Climate Change, 2020) and crucial to the grid's transition to net-zero (National Grid ESO, 2020).

Over the operation of the solar PV systems, a panel degradation rate of 0.5% per year is assumed, assuming that the system undergoes routine maintenance checks (Greenmatch, 2020). The panels are assumed to be replaced every 30 years; however, the end-of-life route of the decommissioned solar panels is excluded from the scope of this study.

Rail-interaction with a steadily decarbonising grid

National Grid, the UK's primary energy supply operator, achieved a reduction in direct GHG emissions of about 68% in 2020, compared to the 1990 baseline (National Grid, 2020). In 2020, renewable resources made 42% of our energy mix, outstripping the non-renewables contribution. The UK's largest electricity supplier is on route to achieving 70% reduction by 2030 and 80% by

2050. This is likely to have a significant impact on the asset's whole life carbon, particularly with almost 42% of the tracks in the UK having been electrified so far (Office of Rail and Road, 2020).

National Grid, in collaboration with key industrial stakeholders, published the 'Future Energy Scenarios 2020' (FES2020), which explores a range of pathways employing a combination of feasible and disruptive energy supply tech, that could potentially assist the sector in achieving net-zero by 2050. The aim of this model is to help industries and other sectors explore and model the extent to which the energy and heat they use could be decarbonised, with and without technological adoptions, societal acceptance and behavioural changes.

The four pathways developed and analysed within FES2020 include the following:

Steady Progression: The slowest possible route to decarbonisation, involving only power generation and transport, excluding heat, and with minimal behavioural change.

System Transformation *(a net-zero pathway)***:** The third fastest route to decarbonisation where the initiative lies with the integration of innovation at the supply side; Fossil fuels are effectively replaced by electricity and hydrogen, mainly for heating and transport, while the energy demand from the consumer side remains the same. Hydrogen use dominates the energy supply in this scenario (fulfilling 59% of all demand), compared to electricity. However, for rail transport, electrification is still considered the most ideal. Integration of a mixture of hydrogen and electrification and significant bioresource use for energy generation via BECCS (Bioenergy with Carbon Capture and Storage) is assumed to deliver a carbon-negative energy supply. On the other hand, energy demand from the consumer side is expected to take a slower progression as opposed to the immediate societal adaptation assumed in the following pathways.

Consumer Transformation *(a net-zero pathway)*: The second fastest route to decarbonisation, in which there are significant societal changes, higher levels of energy efficiency, and lower energy demand. The energy systems modelling based in this pathway hinges on ambitious modal shift assumptions (switches to public transport and more active modes), complete electrification of private and public vehicle fleet etc. Strategies from the consumer side also include installation of residential heat pumps; carbon capture, usage and storage (CCUS) facilities at industrial and commercial sites; and bioenergy use. Integration of a mixture of hydrogen and electrification and significant bioresource use for energy generation via BECCS (Bioenergy with Carbon Capture and Storage) is assumed to deliver a carbon-negative energy supply.

Leading the way *(a net-zero pathway)*: The fastest route to decarbonisation where both the supply and the demand side show significant positive changes, functioning at the highest possible efficiency. Immediate uptake of sustainable technological solutions coupled with major changes in the energy policy landscape is assumed in this pathway. Integration of a mixture of hydrogen and electrification for home heating and significant bioresource use for energy generation via BECCS (Bioenergy with Carbon Capture and Storage) is assumed to deliver a carbon-negative energy supply by 2026.

The sources of the electricity mix for the various scenarios from 2020 to 2050 have been presented in the Table 2. The corresponding carbon intensity for the electricity mix generated from the different pathways was assumed for the embedded carbon estimation of sub-systems that are directly reliant on the electricity grid.

Electricity mix	**Steady Progression**				**System Transformation**			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Biomass	9.1	1.8	1.5	1.4	9.4	2.1	0.3	0.2
BECCS	0.0	0.0	0.0	0.0	0.0	1.2	10.4	8.8
Fossil Fuel	36.8	14.9	17.4	12.2	34.1	12.4	0.4	0.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	1.6	2.4
Nuclear	19.0	17.3	8.7	12.5	21.2	12.5	18.8	14.8
Offshore Wind	12.2	32.8	43.6	50.0	12.2	35.9	45.2	52.4
Onshore Wind	11.1	18.0	15.2	12.1	11.2	18.6	11.0	7.9
Other Renewables	7.6	9.8	7.5	6.3	7.6	9.8	4.6	6.3
Solar	4.1	5.4	6.1	5.5	4.2	7.5	7.6	7.2
Note: The carbon intensity for the energy supply, from each of these scenarios are being applied only to rail ‘operation’ and ‘maintenance’ sub-systems, over the 40 years of assumed service life, while the energy mix and its carbon intensity for the present year (2021) of the ‘Steady Progression’ scenario is applied for material processing and construction.								

Table 2: Electricity mix (in % contribution) over the different pathways (2020-2050) (National Grid ESO, 2020)

It is evident from the review of these energy scenarios that the net-zero strategies are dependent on factors that are not directly under the energy sector’s influence: consumer engagement and societal behaviour change. Understanding, modelling and adopting the complexities of consumer acceptance and behaviour is outside the scope of this analysis. Hence, this study proceeded to adopt two pathways which are representative of the energy systems evolution towards the production and supply of low-carbon energy. The adopted pathways are ‘Steady Progression’ and ‘System Transformation’.

The variety in the energy mixes predicted for the temporal boundary of this analysis (40 years) will reflect the carbon intensity of the energy sources across the adopted pathways (from 2020 to 2060). Subsequently, the carbon intensity of the energy mixes is expected to have a huge influence on the ‘track-operation’ sub-system which may be directly reliant on the grid for power supply. We explored the variations in the electricity mix and the subsequent carbon impact of this variation on the whole life carbon of the built assets adopted for this analysis. It is to be noted that the grid decarbonisation pathways have been applied only for the ‘track-operation and maintenance’ sub-system.

Within any energy-use emissions modelling, it is vital to assume a setting where negative carbon acquired from technologies employing carbon-capture and storage (for example, BECCS[2] and/or DACCS[3]) are to be allocated for hard-to-decarbonise sectors such as aviation and agriculture. Therefore, the net emissions correspond to the cumulative direct GHG emissions resulting from construction, maintenance, and operation of the schemes, without assuming any carbon-negative contributions from the decarbonised electricity mix. This setting will be referred to as a ‘no CCS’ setting. Nevertheless, for the purpose of exploring the extent to which decarbonisation could be achieved, this study also explores a ‘CCS’ setting where transport infrastructure acquires access to negative carbon produced by the technology mentioned earlier.

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[2] BECCS: Bioenergy with Carbon Capture and Storage

[3] DACCS: Direct Air Carbon Capture and Storage

3 Impact assessment – Result interpretation

The whole life carbon and energy use attributed to the resource consumption within the construction, operation and maintenance of 1 km of the ballasted and ballastless tracks have been presented in Figure 3 and Figure 4. Assessing the capital and operational carbon of the sub-systems, the maintenance of the rail track is relatively carbon-intensive, contributing 70% of the whole life carbon. The embodied carbon in the materials and the construction process (embodied carbon) jointly contribute just 27%. A significant proportion (about 58%) of the whole life carbon comes from the 85% virgin steel used in the rails, fastening clips and the steel sleepers, during both construction and maintenance of the asset. This was observed despite the dominance by volume of gravel and concrete use (for the ballast and the track bed pavement). On the other hand, we are assuming that the fastening clips and rails are renewed every 20 years, which adds to the whole life carbon burden, as a part of the operational emissions. These outcomes tend to be sensitive to end-of-life treatment of the recovered steel and concrete components. Therefore, the overall life cycle emissions of the rail infrastructure would be reduced if the present practice of re-using recycled steel were to be intensified, and included into the system boundary of this study.

On the other hand, ballastless tracks are concrete-heavy alternatives to the traditional ballasted tracks. Therefore, their embodied carbon is 39% higher than their traditional counterpart. However, the promise of a longer service life, stemming from the long-term structural integrity from resistance to load vibration and alignment stability, requires these tracks and rails be replaced only once every 60 years. As opposed to the various components that need replacing in a ballasted track (ballast, sleepers, fastening clips, insulators, and the rail), ballastless tracks need virtually little to no component replacement. This leads to a 50% drop in operational carbon, compared to the traditional ballasted tracks. Comparison of the material and thus the carbon trade-offs between the two types of tracks may be beneficial and significant only when accounting the end-of-life specifications of the track components that have undergone replacement. Network Rail has dedicated component recycling plants across England, where components that have reached the end of their functional life are repurposed and used. Reintroduction of recycled components such as steel, ballast and concrete could reduce the whole life carbon of the assets significantly. However, there is too little clarity in the open literature and via the official sources, for relevant analysis on these aspects to be included in the current scope.

The sub-system that contributes to the highest level of uncertainty here is ‘material transport’. Owing to limited access to primary data on the supply-chain and logistics of the material acquisition, this study employs appropriate assumptions to the transportation modes and distances (drawing from the location of potential construction sites and closest available maintenance/supply depots). Therefore, uncertainties in these assumptions could contribute to variations in the ‘material transport’ phase in future analyses.

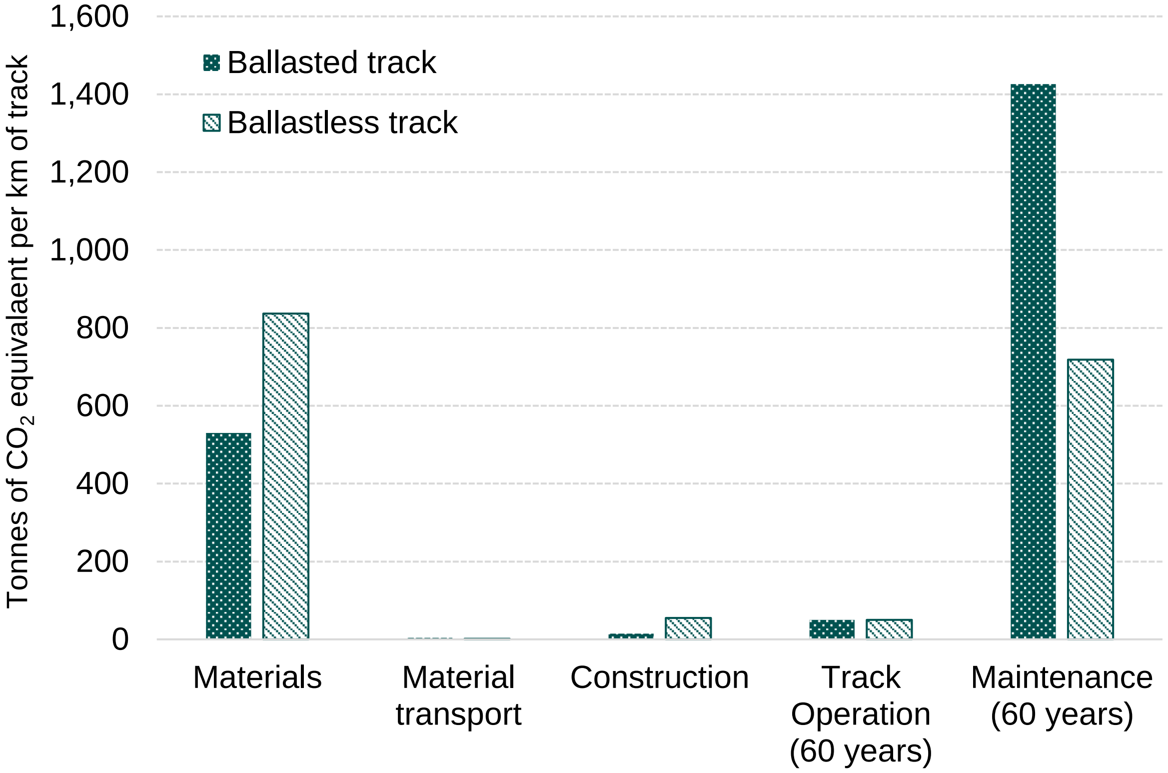

Figure 3: Embodied and operational carbon of 1 km of ballasted and ballastless tracks

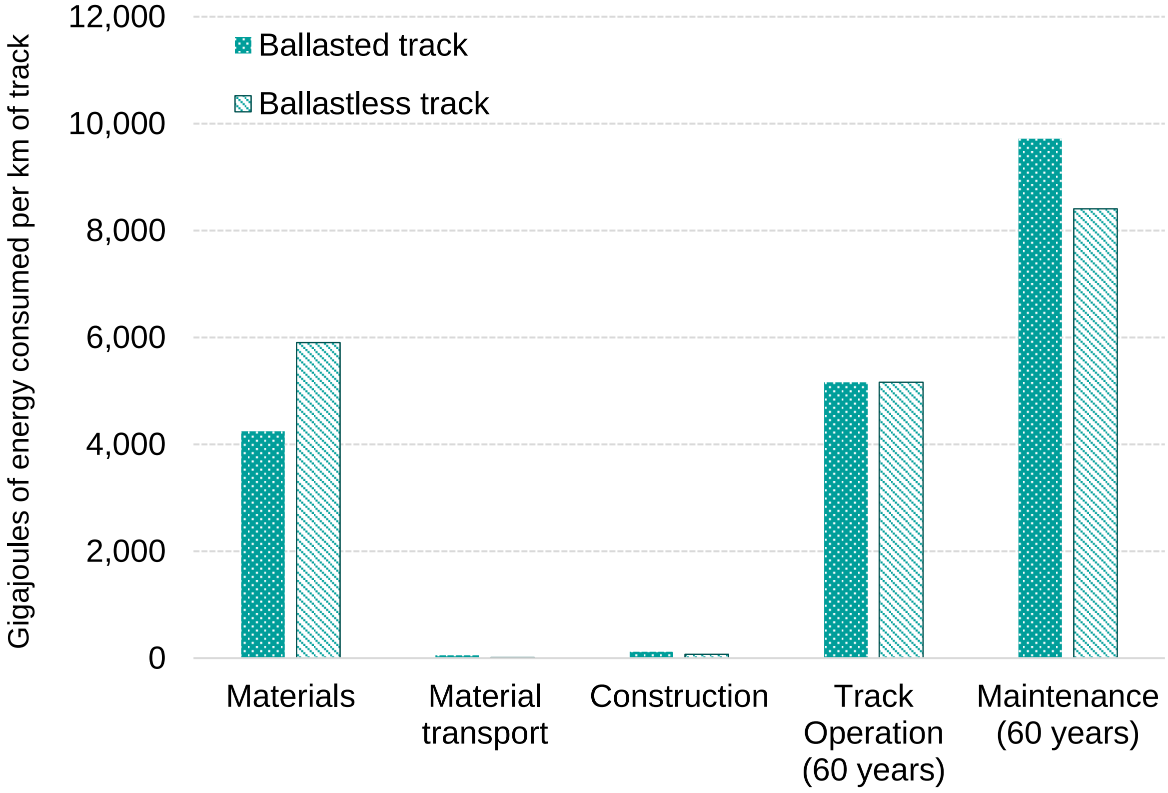

Figure 4: Embodied and operational energy of 1 km of ballasted and ballastless tracks

The whole life carbon impacts of the infrastructure components in the upcoming sections are estimated for both indicative purposes and for application to the three case studies in later sections of this report. The whole life carbon impacts of these components have been presented in Table 3.

Parameters	Electrified Single-track	Standard U-style Overbridge	S&Cs	Platform extension
Distance	1 km	20 m	67.5 m	700 m
Unit	tCO_2eq	tCO_2eq	tCO_2eq	tCO_2eq
Materials	256.13	177.9	147.03	978
Material transport	0.15	24.35	0.12	0.06
Construction	-	165	235.77	932
Operation (60 years)	879.03	-	5.15	275.14
Maintenance (60 years)	561.01	14.05	441.08	45.3
Total emissions	1,696.32	381.31	829.13	2,230.5

Table 3: Whole-life carbon impacts for components of a rail-transport corridor

The estimated whole life carbon of the functional unit of this study, over its life-period of 60 years, is comparable to that reported in published literature (Hill et al., 2012; Kiani et al., 2008; Pons et al., 2020). The temporal boundary assumed within the literature was similar to that assumed here. There were minor variations in the assumptions and the parameters of the system boundaries, particularly where the asset management included landscape, signage and signal maintenance, along with the inclusion of user-emissions (vehicle operation). The former is excluded from this analysis since its overall contribution was deemed trivial compared to those that were included. User-emissions were excluded, since they are likely to be categorised as user-operational emissions, as opposed to infrastructure-operational emissions. The percent variation between the estimated whole life carbon for our built asset (1 km of single rail track) was compared to the outcomes of the other studies The benchmark whole life carbon estimates in this report are observed to be about 4.4 to 8.2% higher than those reported in other published literature (Hill et al., 2012; Kiani et al., 2008; Merchan et al., 2020; Pons et al., 2020).

3.1 Sensitivity study

Low environmental impact and commercially viable alternatives

Recycled composite sleepers (employing recycled plastics and powdered rubber from disposed tyres) were observed to deliver the highest carbon savings (10-15%) among the other candidates, compared to traditional concrete sleepers (Figure 5 and Table 5). Despite the use of secondary resources, the concrete used to build the inner core of sleeper for reinforcement was still the more carbon-intensive component. According to the studies, the structural functionality of the recycled composite sleepers, for example, resistance to abrasive damage from the underlining ballast and the long-term mechanical integrity, was comparable to traditional concrete sleepers, extending their service life to 35 years (see Table 4). However, data on their performance over their service-life is not available in the open literature due to the novel nature of these sleepers. As a result, this study factored in the uncertainties around the expected service life and evaluated scenarios where the sleepers may require replacement every 20 and 30 years, following a methodology employed by (Dolci et al., 2020). The changes in the whole life carbon of 1 km of ballasted track employing these alternative sleepers were determined to be between +3.7% and -2.4%, compared to that of the traditional sleepers over their 35-year life span. These savings are likely to be significantly higher in the event of wider uptake of secondary materials or via complete replacement of concrete sleepers with more sustainable alternatives as suggested within the Network Rail Environmental Sustainability Strategy 2020-2050 (Network Rail, 2021e). As before, however, lack of clarity in the published literature on the ideal end-of-life route for the components of these alternative sleepers (inner core and plastic-rubber composite) casts uncertainties on their long-term environmental performance, unlike their traditional counterparts which are efficiently recycled (Network Rail, 2021b).

Fibre-reinforced foamed urethane (FFU) are synthetic alternatives to the conventional hardwood and concrete sleepers. Evaluation of the material’s carbon burden showed that the embodied carbon of the alternative sleepers was twice that of the traditional sleepers. However, at a whole life level, the proven structural integrity demonstrated by these sleepers so far (Demiroglu, n.d.; Gholamali et al., 2019; Koller, 2015; Kuranchie et al., 2021; Sengsri et al., 2020) have suggested that the sleeper’s service life is more than 75 years, going 15 years beyond the temporal boundary of this study. This significantly reduces the maintenance requirements, particularly additional wooden sleeper requirements over the whole life period. An overall analysis, however, showed that the use of FFU sleepers in 1 km ballasted track is 13% more carbon intensive compared to conventional concrete/wooden sleepers. However, the whole life cycle of these sleepers (including their end-of-life specifications) must be taken into account to be conclusive of the carbon balance. The FFU sleepers have been reported to be 100% recyclable by studies including (Gholamali et al., 2019; Koller, 2015; Lu et al., 2019; Sengsri et al., 2020), thus improving their relative long-term environmental credentials. A lack of comprehensive studies into the direct and indirect effects from use of FFU sleepers (such as dissipation of granular material from load and stress, abrasion with the ballast bed, particulate leakages into soil and drainage water) causes these findings to be inconclusive. It is crucial to note that these impacts are quoted as preliminary estimates and are for informative purposes only.

Sleeper type[1]	Embodied carbon ($kgCO_2eq$)	Embodied energy (GJ)	Replacement frequency[2]
Baseline - Concrete sleepers	64	1.9	every 30
Recycled composite sleepers	81	2.1	every 35
Synthetic FFU sleepers	450	7.1	>75

Note:

[1] Embodied carbon and energy estimates correspond to a unit of sleeper (1 no.)

[2] in years; Source: Dolci et al., 2020; Ferdous et al., 2021; Kiani et al., 2008; Rempelos et al., 2020; Yu et al., 2021

Table 4: Embodied carbon and energy data for alternative sleepers considered in the sensitivity study

Sensitivity study- Alternative materials	**Baseline**	**RE_Scenario_1**	**RE_Scenario_2**	**RE_Scenario_3**
	Concrete sleepers	Recycled Composite sleepers	FFU sleepers	Concrete and FFU sleepers
Distance	1 km	1 km	1 km	1 km
Unit	tCO_2eq	tCO_2eq	tCO_2eq	tCO_2eq
Materials	529.00	442.00	1,071.00	508.60
Material transport	3.95	3.95	3.95	3.95
Construction	14.26	14.26	14.26	14.26
Operation (60 yrs)	50.17	50.17	50.17	50.17
Maintenance (60 yrs)	1,426.00	1,201.00	1,151.00	1,426.00
Total emissions	2,023.38	1,711.38	2,290.38	2,002.98

Table 5: A comparison of embodied carbon estimates for the different resource efficient scenarios over an assumed 60-year life period.

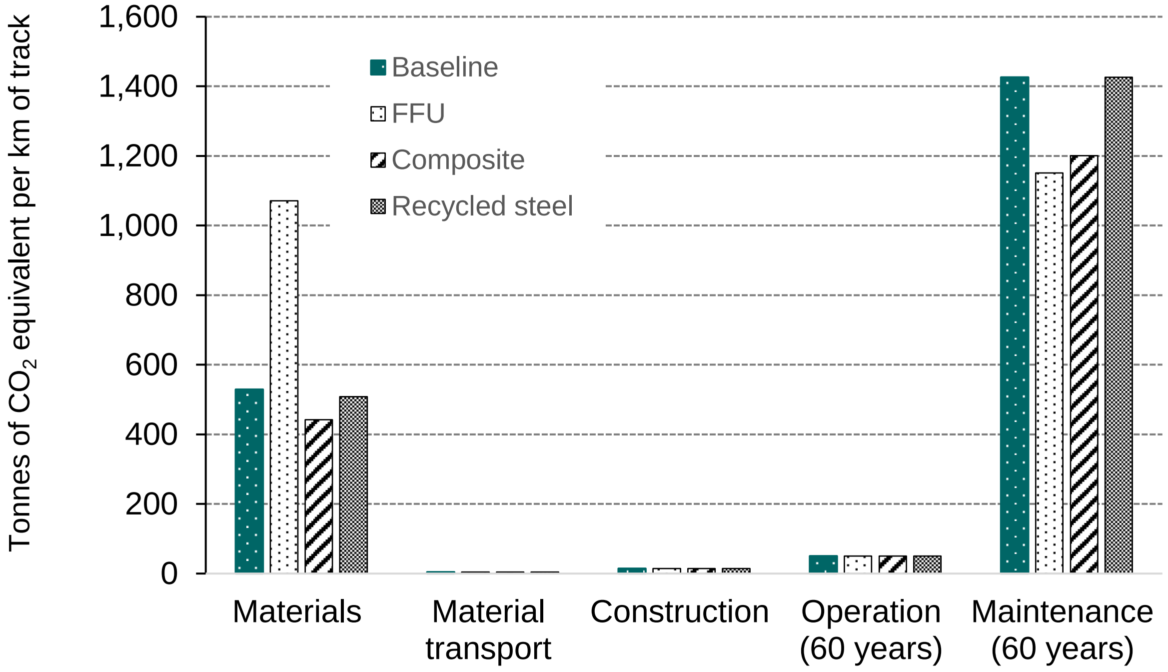

Figure 5: Sensitivity of the embodied carbon of a 1 km of ballasted track (baseline) to the integration of low-carbon alternative materials and technology

Installation of Solar PV energy systems

This is a section of the analysis which is mainly restricted to the case study application, particularly encompassing those that involve platform extension and station upgrades presented in the upcoming sections 0 and 4.2. However, an overall analysis providing guidance on the range of carbon savings that can be acquired from integration of PV systems has been provided. Stations that were planned for upgrades, including platform extension and refurbishment, are assumed to include an additional upgrade involving installation of a solar PV system to generate sustainable energy for their operation over the assumed period of over 60 years. In our study, the operational carbon emissions are calculated mainly based on heat and electricity demand. Therefore, the capability of PV-derived electricity to save operational carbon over the temporal boundary of this study, and potentially to payback the embodied carbon of the installed solar PV systems has been assessed and discussed.

Installed PV systems, operating at a current average panel efficiency of 20% under average weather conditions and solar output for the North of England (1,500 hrs of sunlight per year), 1 m^2 panel could generate 300 kWh per year. The carbon savings from displacement of grid electricity[4] with clean sustainable solar PV electricity could, on an average, save 14.8 tCO_2eq per year. This negative 'operational carbon' could pay off the embodied carbon of the PV panels in about 2 years of installation. The subsequent savings in CO_2 emissions, calculated by applying the carbon intensity of the displaced grid electricity to the PV array's whole life carbon, over the life of the solar array assumed in this study (60 years), is in the range of -150 to -650 tCO_2eq, depending on the installed capacity[5].

Applying a panel degradation rate of 0.5%, and assuming routine maintenance for the panel array's optimal functionality, installations of 23-96 kWp deliver a lifetime electricity supply of 106-440 MWh (megawatt hour). This corresponds to 1,760-7,300 kWh per year from the installed capacities. Net carbon savings acquired from deducting the station's energy use over an assumed period of 60 years, is determined to be in the range of 50-1,500 tCO_2eq, capable of having a positive impact on the operational and subsequently the whole life carbon of the planned scheme (built asset).

Integration of a rapidly decarbonising grid

Impact of grid decarbonisation on operational carbon (track operation incl. OLE, S&Cs)

Investigations into the sensitivity of the asset's operational carbon to the impact of a rapidly decarbonising electricity grid has been undertaken. With 38% of the UK's rail lines electrified and more underway, the long-term transition to low-carbon and subsequently, to a net-zero energy grid, will have a major impact on the operations of the rail infrastructure. The rail sector is currently responsible for approximately 2% of the overall transport-related energy consumption and 1% of carbon equivalent emissions in the UK (National Grid ESO, 2020).

There are variable levels of electricity consumption observed among the components of rail infrastructure over their functional life. For example, a functional unit of ballasted tracks, on their own consume little to no energy supply. However, there are other rail components such as switches and crossing (S&Cs), OLE support structures, and buildings such as stations, platforms and auto-transformers that require uninterrupted electricity provision. Therefore, these components have been accounted for this sensitivity analysis, excluding signalling and communication, workshop operation and train control.

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[4] Steadily decarbonising grid electricity assumed: 'Steady Progression' pathway from FES2020 has been applied to the solar-derived carbon intensity calculation over a temporal boundary of 60 years.

[5] For the purpose of this hypothetical analysis, we are assuming ideal structural specifications for the rooftops on which the solar PVs are assumed to be installed (south-facing, inclination, annual exposure rate and yield efficiency applicable for the North of England etc.).

The combined capital and operational carbon of 1 km of overhead line equipment (OLE), is determined to be 1,696 tCO_2eq per track km and requires an appropriate electricity supply of about 47 MWh per year, based on the assumptions of its operation (section 2.1) and relevant data available from published literature (Hill et al., 2012; Uglešić et al., 2009). The operational carbon which corresponds to energy use for the operation of S&Cs, signalling and OLE electrification, assumed corresponding to 1 km of the single track, was observed to be offset by the overall carbon neutral energy supply from 2040, under the 'System-Transformation' pathway. On the other hand, under the 'Steady Progression' pathway, the low-carbon energy supply delivered carbon savings in the range of 60-84%.

These net emissions were combined with the overall embodied carbon of the OLE support structures for two purposes:

- to assess the sensitivity of the asset's whole life carbon to a steadily decarbonising grid and
- to compare the estimated carbon under a 'CCS' and 'no CCS' settings

As mentioned in section 0, the carbon savings acquired from the integration of 'carbon negative' technologies, such as BECCS and DACCS, will need to be allocated to the budgets for 'hard-to-decarbonise' sectors such as aviation and agriculture. As a result, the transport sector is required to reach absolute-zero by 2050, where inter-sectoral carbon allowances or trading would not be possible.

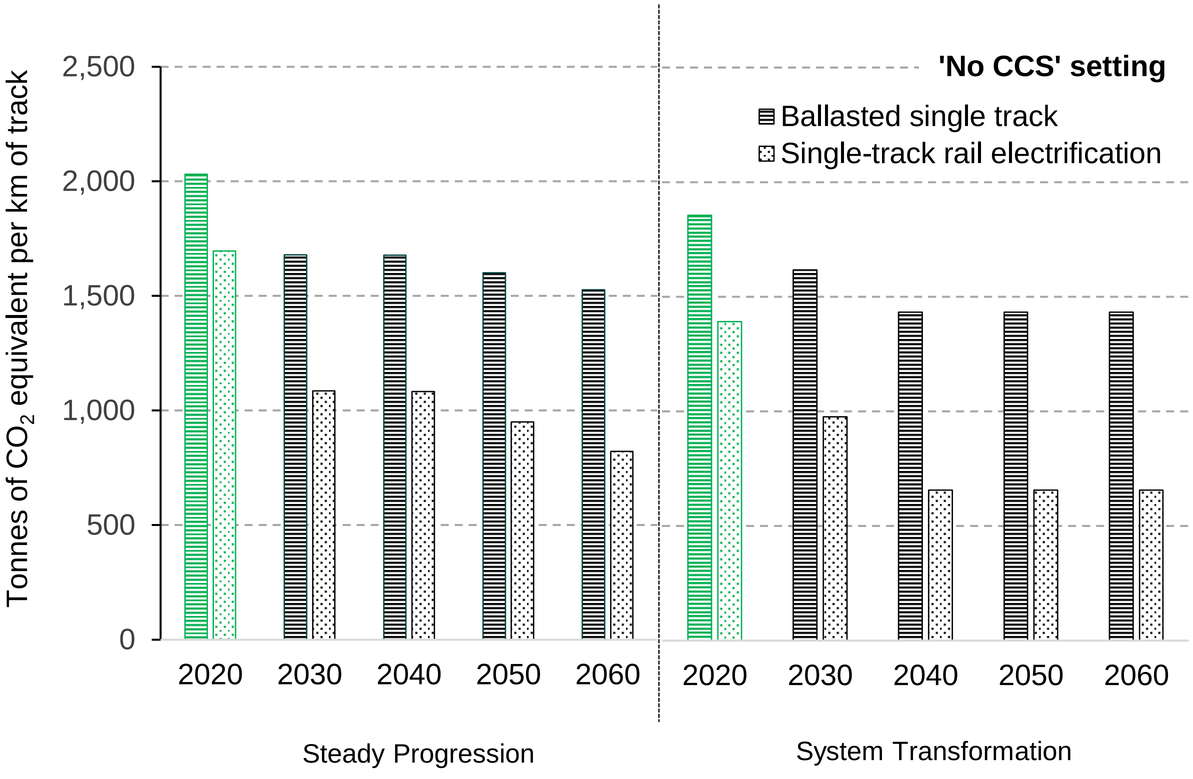


Figure 6: Combined embodied and operational carbon impacts of 1 km of an electrified single-track for between 2020 and 2060, under the 'no CCS' setting (Note: progression to 2080 excluded due to lack of data) (Note: Baseline scenario highlighted in green)

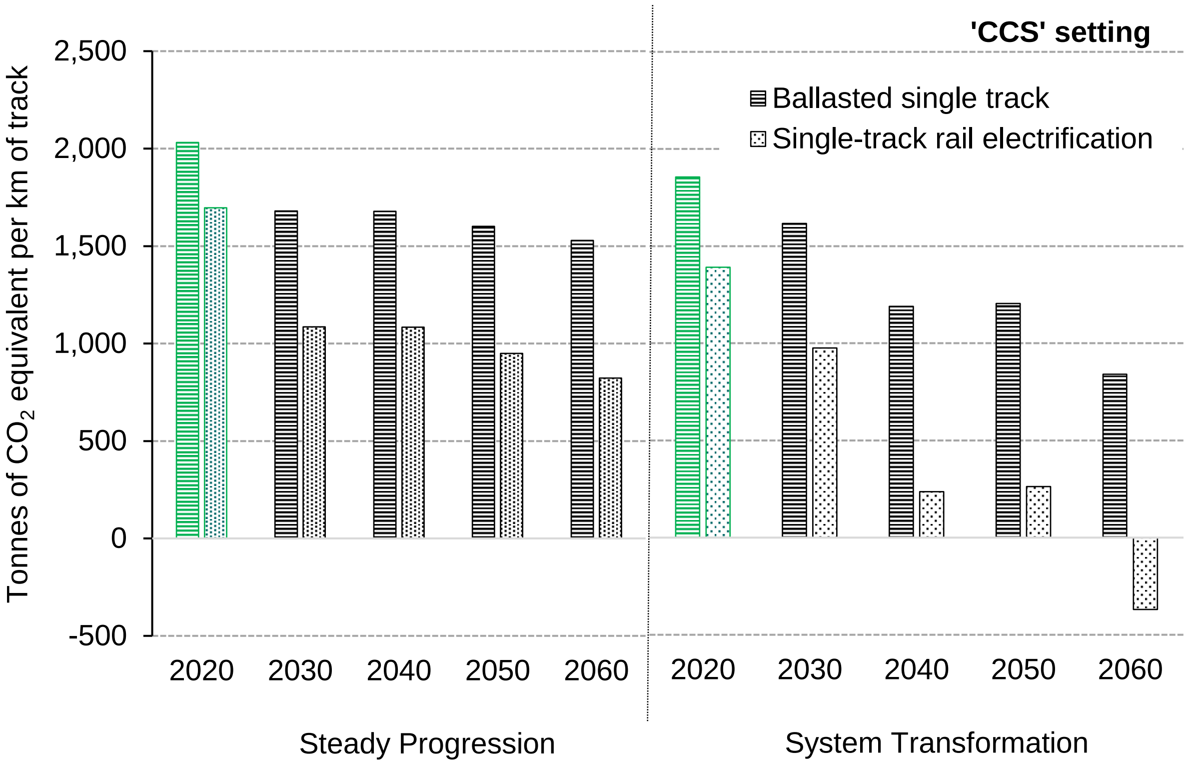


Figure 7: Combined embodied and operational carbon impacts of 1 km of an electrified single-track for between 2020 and 2060, under the ''CCS' setting (Note: Baseline scenario highlighted in green)

This will be referred to as the 'no CCS' setting in this study. For illustration, we include a scenario where the transport sector, similar to the other sectors, acquires access to the carbon-negative emissions from these technologies and is able to abate some of the hard-to-decarbonise sub-components of its infrastructure, mainly construction materials. This has been referred as 'CCS' setting in Figure 7. However, we do not discuss this further as it is outside of the understood potential for CCS as set out by the Climate Change Committee.

Applying the carbon savings from earlier to the whole life carbon emissions, the overall corresponding carbon savings were in the range of 12-22% and 25-62% under the 'Steady Progression' and 'System Transformation' pathways. This corresponds to the outcomes of the 'no CCS' setting (Figure 6). The significantly lower carbon intensity comes from the deployed low-carbon energy systems, supported by a robust energy policy landscape that has been assumed in the 'Future energy scenarios' modelling. For example, the 'Steady Progression' pathway adopts the slowest pace for transformation in the technological innovations, their uptake, policy-driven industrial and consumer behavioural/lifestyle changes. As a result, there is a steady and significant reliance on fossil fuels (natural gas) for electricity supply, right up to the net-zero target date. This represents a huge challenge to low-carbon energy generation, supply and eventually decarbonisation of affected sectors, thus representing a scenario where we fail to reach net-zero by 2050.

A significant proportion of electricity is used for station operation, electrification of OLE and operation of switches and crossings (S&Cs) commonly found in the vicinity of rail stations, key nodes of the rail-routes and the wider network. Having well over 20,000 S&Cs in the rail network, with an expected annual electricity consumption of roughly 400 kWh per S&C unit, a significant amount of electricity is required to operate and maintain these systems over the assumed service life (60 years) (Coleman and Cornish, 2010; Hill et al., 2012; Merchan et al., 2020). Similarly, rail stations show an adjusted electricity consumption at a range of 0.04-0.06 kWh/passenger per year (based on data from Hill et al., 2012). A decarbonising grid, under the 'no CCS' setting, reduced the corresponding operational carbon only from stations by about 5-18% under the 'Steady Progression' pathway and by about 6-21% under the 'System Transformation' pathway (Figure 8 and Table 6). One of the key observations was that the highest level of savings is observed for stations operating with the highest passenger capacity. Again, for illustration, in the 'CCS' setting, the reported carbon savings under the 'System Transformation' pathway improved to 6-41% for the stations of varying annual passenger patronage (Figure 9 and Table 8). The carbon savings were in the range of 8-26% and 5-17% for passenger stations of 660 thousand and 300 thousand per year capacity.

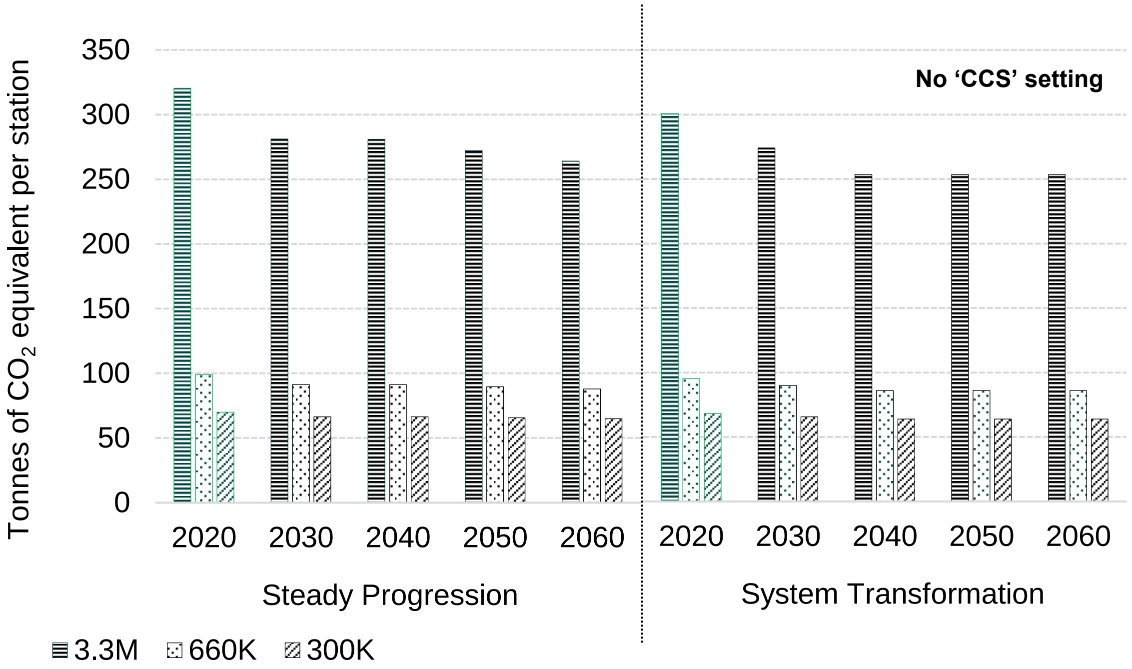


Figure 8: Combined embodied and operational carbon estimated for a rail station of varying passenger capacities (3.3 million, 660 thousand and 300 thousand passengers per year) between 2020 and 2060, applying the carbon intensity of a steadily decarbonising grid, under the 'no CCS' setting (Note: Baseline scenario highlighted in green)

Year	Steady Progression			System Transformation		
	% Op. carbon savings relative to 2020 levels per station of capacity			*% Op. carbon savings relative to 2020 levels per station of capacity*		
	3.3M	660K	300K	3.3M	660K	300K
2030	12.3	7.8	5.1	14.5	9.2	6.0
2040	12.3	7.8	5.1	20.9	13.3	8.7
2050	15.0	9.5	6.2	20.9	13.3	8.7
2060	17.6	11.2	7.3	20.9	13.3	8.7

Table 6: Percent operational carbon savings from a steadily decarbonising grid by one rail station of varying passenger patronage over 2030-2060, relative to 2020 levels, under a 'no CCS' setting

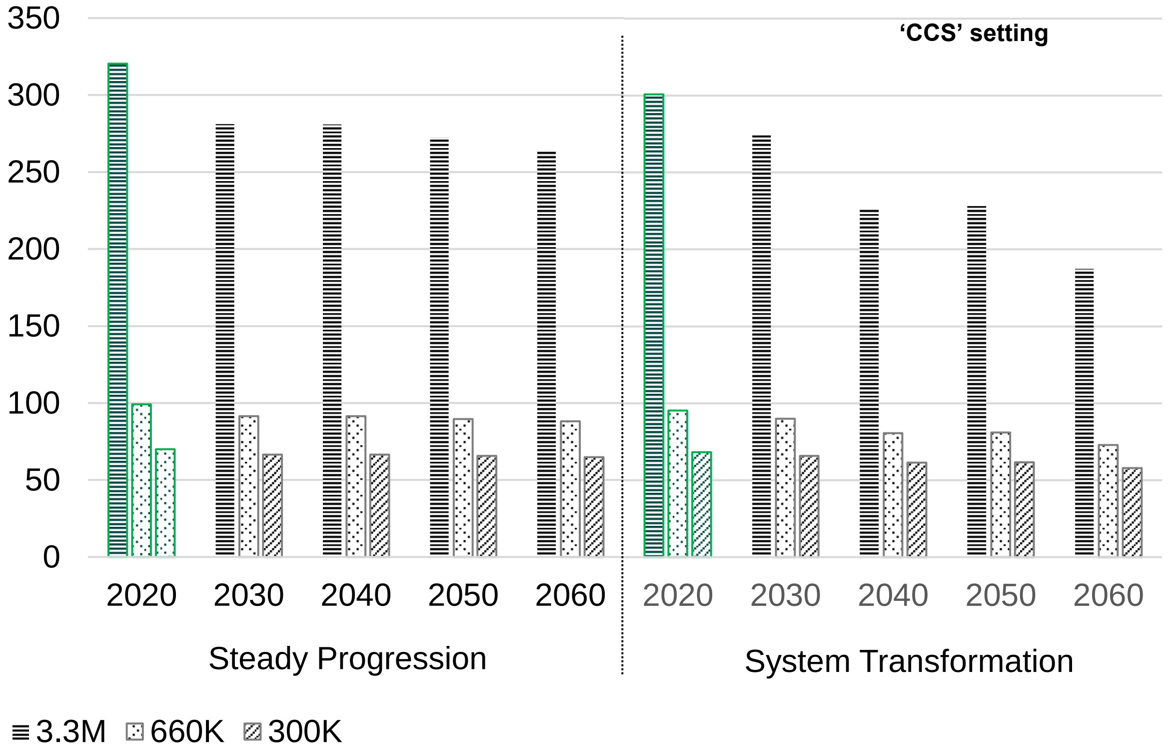


Figure 9: Combined embodied and operational carbon estimated for a rail station of varying passenger capacities (3.3 million, 660 thousand and 300 thousand passengers per year) between 2020 and 2060, applying the carbon intensity of a steadily decarbonising grid, under the 'CCS' setting (Note: Baseline scenario highlighted in green)

Year	Steady Progression			System Transformation		
	% Op. carbon savings relative to 2020 levels per station of capacity			*% Op. carbon savings relative to 2020 levels per station of capacity*		
	3.3M	660K	300K	3.3M	660K	300K
2030	12.3	7.8	5.1	14.5	9.2	6.0
2040	12.3	7.8	5.1	29.3	18.7	12.2
2050	15.0	9.5	6.2	28.8	18.3	12.0
2060	17.6	11.2	7.3	41.5	26.4	17.3

Table 7: Percent operational carbon savings from a steadily decarbonising grid by one rail station of varying passenger patronage over 2030-2060, relative to 2020 levels, under a 'CCS' setting (Note: Strongly relies on CCS – Hypothetical scenario)

Impact of grid decarbonisation on whole life carbon of train stations

Extending these savings to the whole life carbon estimates, the decarbonising grid delivered the following whole life carbon savings between 2030 and 2060, as presented in Table 8 ('no CCS' setting) and Table 9 ('CCS' setting). Analysing the differences in a decarbonised grid's contribution to reducing overall carbon footprint of the intervention (or planned scheme), significant amounts of operational carbon emissions alone are observed to be abated (by up to 85% under 'no-CCS'). However, these savings are significantly diluted when extending these impacts to whole life carbon. Even with the most optimistic scenario, there is a 60-90% of whole life carbon that should be alleviated to achieve carbon neutrality. The primary carbon contributor here is the embodied emissions from material consumption. This is particularly relevant to structures that either employ materials of relatively high embodied carbon (for example, steel used in tracks, S&Cs, and catenary components for the OLEs) or high quantities of construction and maintenance material over the temporal boundary of this study (for example, construction and maintenance of stations, platform extensions).

Year	Steady Progression			System Transformation		
	% WLC savings relative to 2020 levels per station of capacity			*% WLC savings relative to 2020 levels per station of capacity*		
	3.3m	660K	300K	3.3m	660K	300K
2030	2.96	0.59	0.33	3.48	0.70	0.39
2040	2.97	0.59	0.33	5.03	1.01	0.56
2050	3.61	0.72	0.40	5.03	1.01	0.56
2060	4.23	0.85	0.47	5.03	1.01	0.56

Table 8: Percent whole life carbon savings from a steadily decarbonising grid by one rail station of varying passenger patronage over 2030-2060, relative to 2020 levels, under a 'no CCS' setting

Year	Steady Progression			System Transformation		
	% WLC savings relative to 2020 levels per station of capacity			*% WLC savings relative to 2020 levels per station of capacity*		
	3.3m	660K	300K	3.3m	660K	300K
2030	3.48	0.82	0.39	2.96	0.70	0.33
2040	2.97	0.70	0.33	7.06	1.67	0.79
2050	3.61	0.85	0.40	6.94	1.64	0.78
2060	4.47	1.00	0.47	9.99	2.36	1.12

Table 9: Percent whole life carbon savings from a steadily decarbonising grid by one rail station of varying passenger patronage over 2030-2060, relative to 2020 levels, under a 'CCS' setting (Note: Strongly relies on CCS – Hypothetical scenario)

4 TfN case study application: Multi-modal transport sub-corridor in Tyne and Wear, South Northumberland

4.1 Case 1: Scheme 92: East Coast main line spur to Newcastle Airport

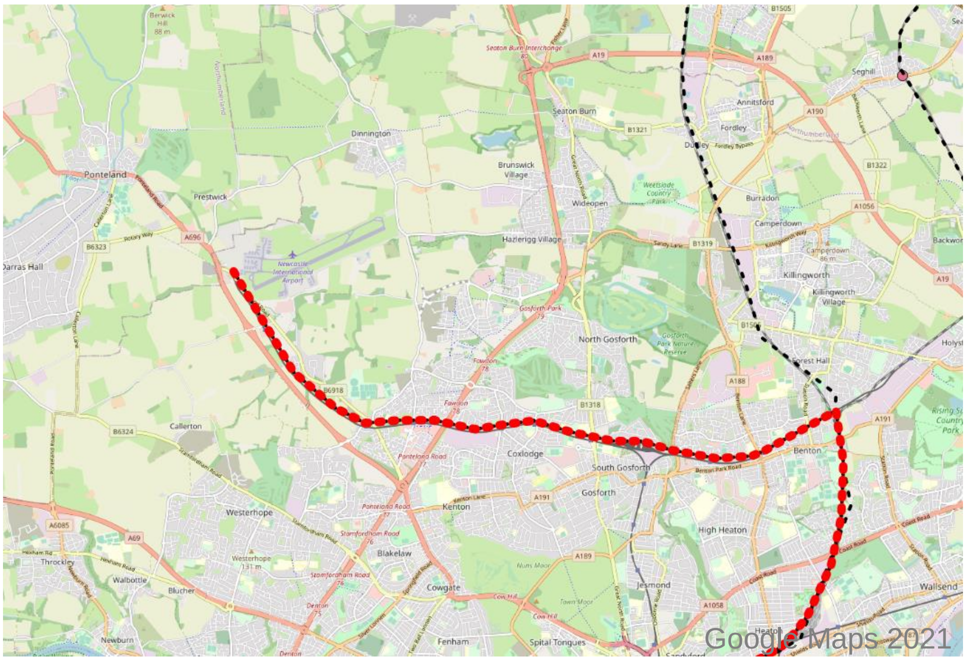


Figure 10: Scheme 92: Planned rail-route – East Coast mainline spur to Newcastle Airport

Temporal boundary	60 years
Spatial coverage	East Coast Main Line, Newcastle upon Tyne, North East England
Route length	7.24 km

Scheme description: The East Coast Main Line (ECML) is a 632 km rail line between London and Edinburgh that is electrified, replacing diesel traction in the 1980s. This is a key rail transport line that runs parallel to the A1, connecting Peterborough, Doncaster, Durham and Newcastle (Figure 10).

Planned developments: The existing mainline is expected to branch out to the Newcastle Airport station, which is currently served by the Tyne and Wear Metro. The new line, which is 7.24 km long, is assumed to be electrified in line with the ECML traction system. To accommodate the branch line, the Newcastle Airport station is assumed to undergo platform extensions from its existing two-track, two-platform to a four-track four platform, supplemented with appropriate waiting rooms, lighting and required furniture. The new line is assumed to be equipped with new ballasted track, and the various road crossings between the airport station and the Newcastle train station are expected to be replaced by new 20 m span standard U-bridges.

Prior to the estimation of embodied and operational carbon associated with this scheme, the resource expenditures over the construction period and operation/maintenance of a built asset, over an assumed service period of 60 years must be understood. Addition of a new line is expected to require vegetation clearance and preparation of land for track bed construction, including the integration of drainage characteristics, installation of overhead line equipment (OLE) and barriers for the separation of construction routes and rail traffic. The approach to whole life carbon estimation of this scheme is parallel to that presented in the benchmark analyses. Similarly, the planned schemes are also subjected to a sensitivity study involving:

- Operational carbon from installation of rooftop solar PV panels for sustainable long-term energy supply
- Sensitivity to a steadily decarbonising grid (under the 'Steady Progression' and 'System Transformation' pathways).

The outcomes of these estimations have been presented in Figure 11.

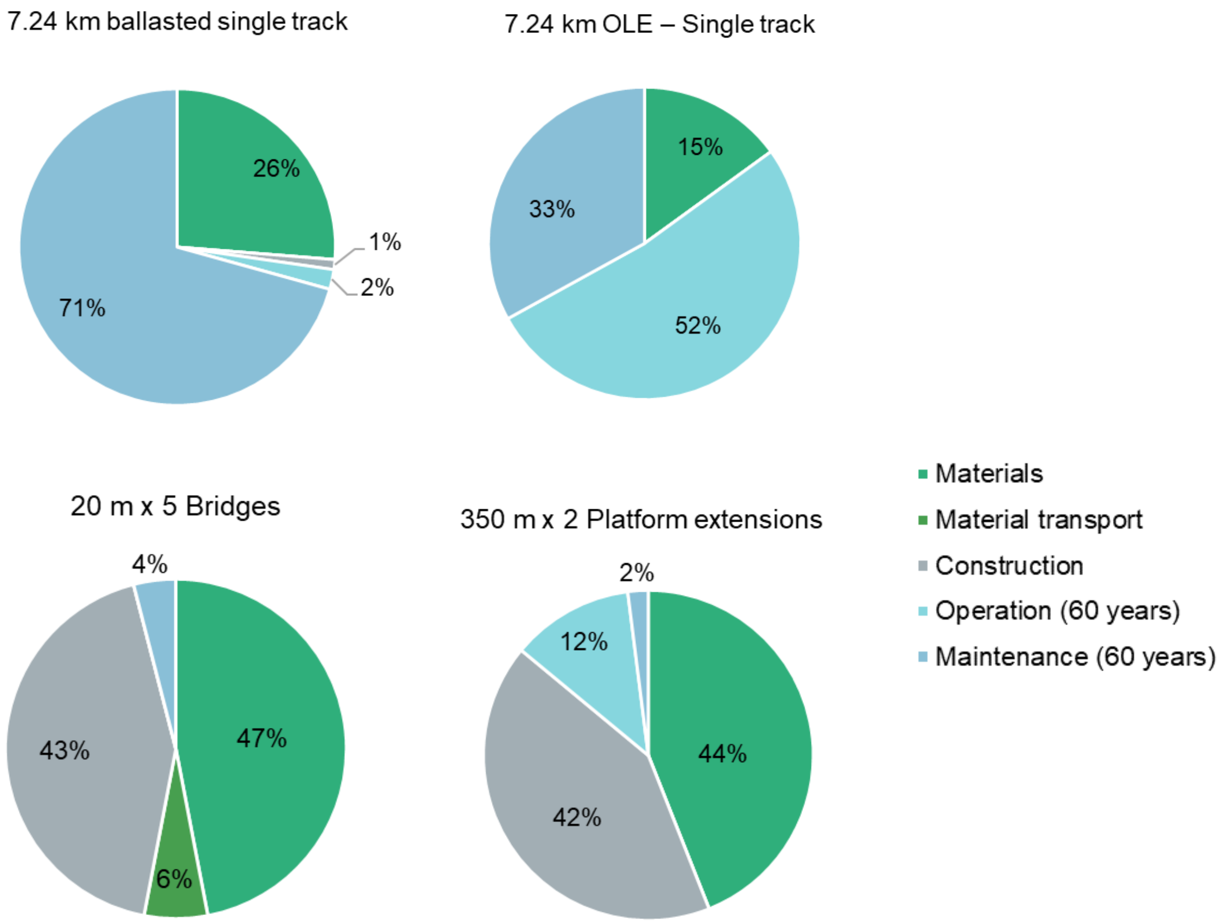


Figure 11: Embodied and operational carbon estimates (% contribution per component emissions) for the different components of the scheme 92 - East Coast mainline spur to Newcastle Airport

The whole life carbon of the all the planned developments in this scheme and the associated structures supporting its installation have been determined to be about 31,073 tCO_2eq. Of this, 9,570 tCO_2eq would relate to the initial construction phase, with the balance over the life of the asset.

The impact of a steadily decarbonising energy grid on the operational carbon, and subsequently, the whole life carbon of scheme 92 is presented in Figure 12 and Figure 13. Under the 'Steady Progression' pathway in the 'no-CCS' setting, the whole life carbon emissions were reduced by about 17-25% for the single-track operation, by about 20-30% for the operation of the electrified track, and by about 0.1-0.14% for the platform extension (due to relatively lower energy use). On the other hand, under the 'System Transformation' pathway in a 'CCS' setting, this whole life carbon savings reduced by about 20-41% for the track operation, by about 36-51% for the electrification and by about 0.1-0.14% for the platform extension.

Within the rail infrastructure, components such as S&Cs, OLEs and the station's energy demand leads to continuous interaction with the national energy grid over the assumed life of the assets. For example, installation of switches at the platforms in the rail station would demand 24 MWh, and the operation and maintenance of the rail station would consume 28-311 MWh of electricity over the asset's service period. Similarly, the OLE for the ECML spur line would need an uninterrupted supply of 20.4 GWh via an autotransformer. Relating to this, the sensitivity of the operational carbon of these components to a steadily decarbonising energy grid that is to deploy low-carbon technologies, investments into overall infrastructure and energy efficiency, is evaluated and discussed in this section. Under the 'no CCS' scenarios, applying the appropriate carbon intensity for electricity mix to the operation of the new tracks (signalling, comms. S&Cs) between 2030 and 2060, the reduction in their whole life carbon was in the range of 17-24% and 20-29%, relative to the 2020 baseline estimates, under the 'Steady Progression' and 'System Transformation' pathways. These reductions further diluted to about 0.1-0.16% when assessing the station's energy demand. Summing up the asset's carbon performance in accordance to TfN's decarbonisation goals, an estimate of 25,117 tCO_2eq, under the 'no CCS, Steady Progression' pathway.

Under the optimistic 'CCS' scenario, which would show any changes only for the whole life carbon reported under the 'Steady Progression' pathway, savings in whole life carbon for all the assets in question were in the range of 20-58% (new single track), 13-38% (track electrification) and 0.1-0.33% (platform operation) respectively. Summing up the asset's carbon performance here, in accordance with TfN's decarbonisation goals, an estimate of 13,596 tCO_2eq, under the 'CCS, System Transformation' pathway. We do not provide an estimate of the equivalent kilometre metric due to the uncertainties surrounding a CCS based pathway.

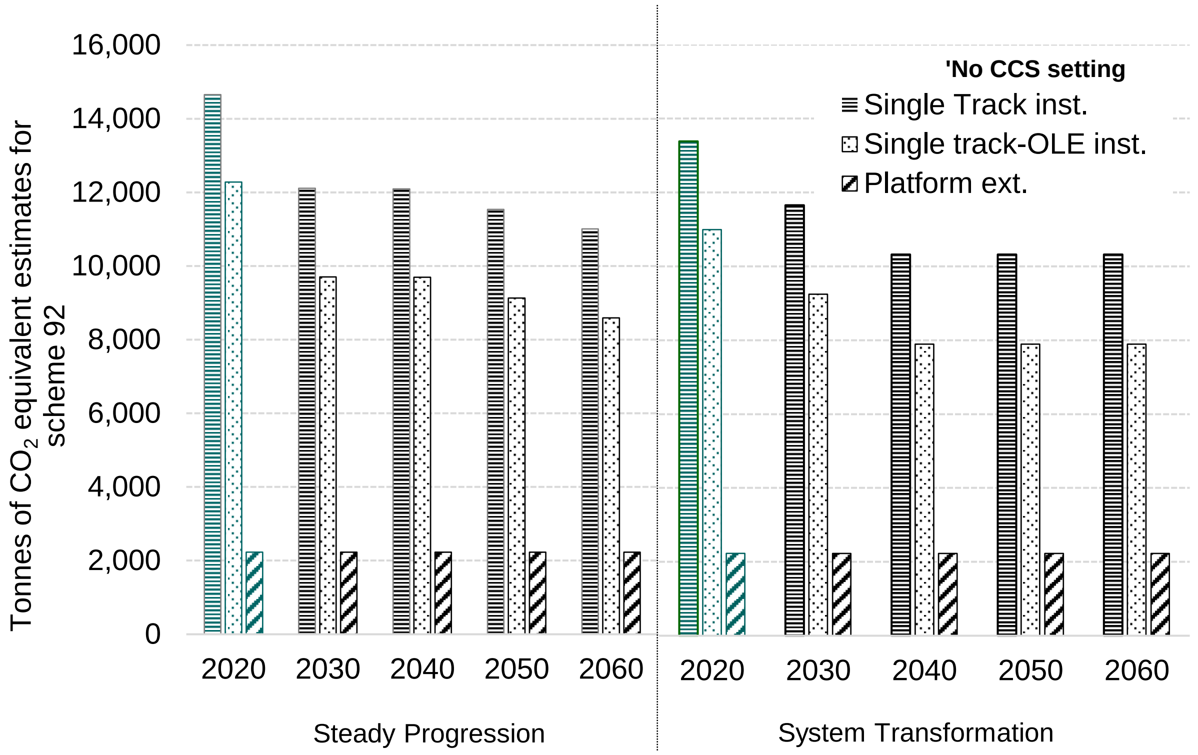


Figure 12: Whole life emissions estimated for scheme 92, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'No CCS' setting

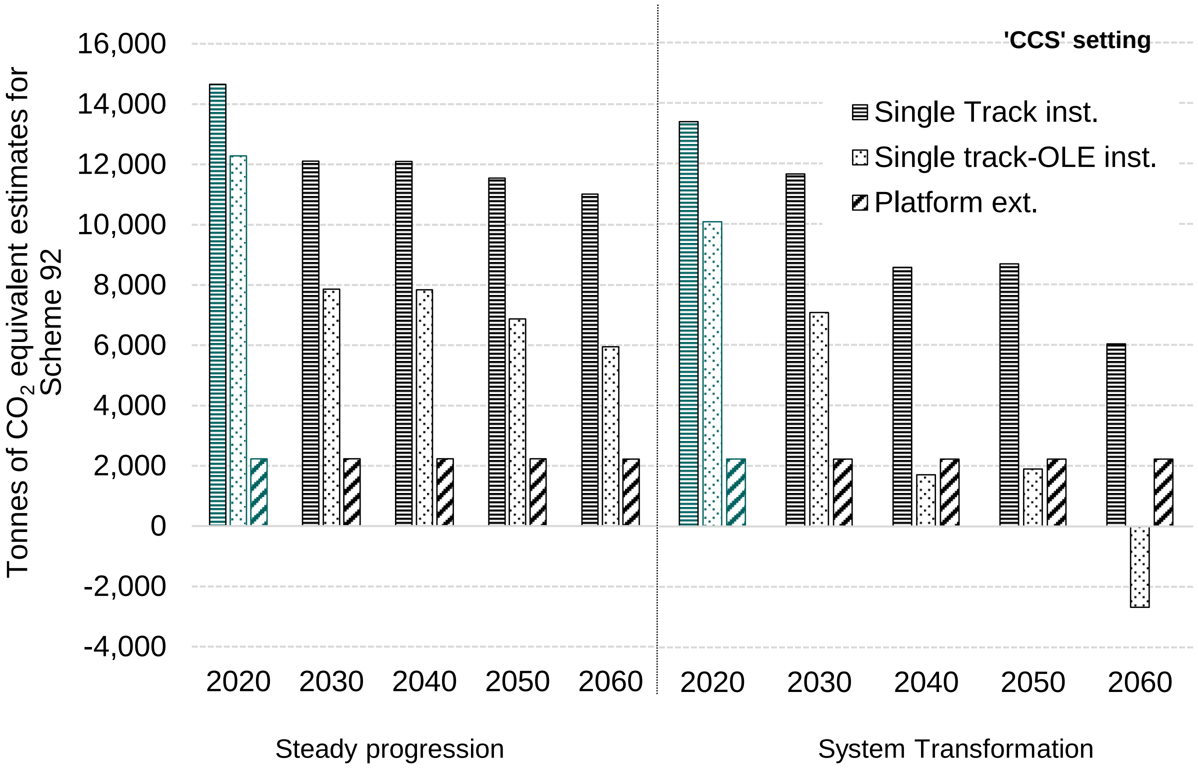
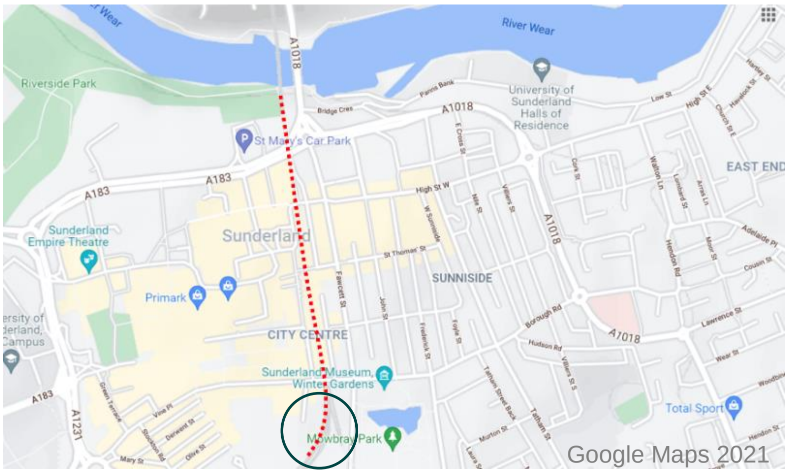
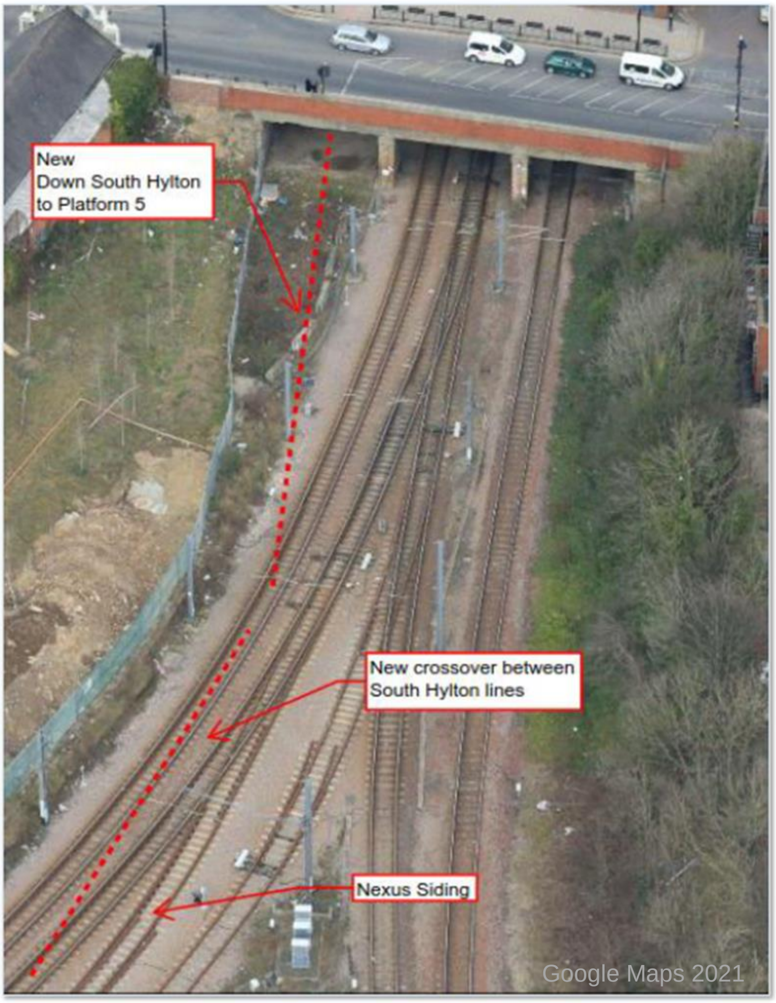


Figure 13: Whole life emissions estimated for scheme 92, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'CCS' setting

4.2 Case 2: Scheme 249: Sunderland Station and Sunderland Station track layout improvements



A new connection from the Down South Hylton line to the new Platform 5 will be constructed via the currently vacant western tunnel portal.



A new crossover will be provided to allow southbound traffic from Platform 5 to access the Up South Hylton line.

Figure 14: Spatial analysis of the planned developments at Sunderland station

Temporal boundary	60 years
Spatial coverage	Durham Coast Line, Tyne and Wear, North East England
Route length	350 m

Scheme description: Sunderland station lies on the Durham Coast Line between Newcastle and Middlesbrough, currently operated and managed by Network Rail and Northern Trains. It has shared its network with Nexus's Tyne and Wear Metro since 2002 and is expected to undergo track extensions to separate the Metro from mainline services (Figure 14).

Planned developments: Though not exhaustive, some of the schemes due for implementation at Sunderland station include reinstatement of platform 5, potential refurbishment and transition of the 2-track 4-platform to 4-track 4-platform. Further developments also include the addition of crossovers towards the south of the station and a turnback siding (additional 250 m track) at Monkwearmouth.

Similar to the work undertaken in the earlier study (Case 1), the whole life carbon of the various components of the schemes were first estimated. Then, the sensitivity of these estimations to the impact of a steadily decarbonising grid were assessed. The whole life carbon estimations from the analysis of the scheme specifications have been presented in Figure 15.

The whole life carbon of the planned scheme for the Sunderland station is estimated to be 3,867.4 tCO_2eq. As opposed to the earlier case study, embodied emissions were the dominant sources of carbon, stemming from the nature of the scheme, which involves station expansion, new track and turnback siding construction. Using the data from Table 10 (see Appendix), we estimate that the equivalent vehicle kilometres per annum that would need to be removed to break even with the embodied carbon would be 2.9 million. The average resident in the North East drives 4,771 km per year so the embodied carbon would be equivalent to 607 people giving up car driving completely.

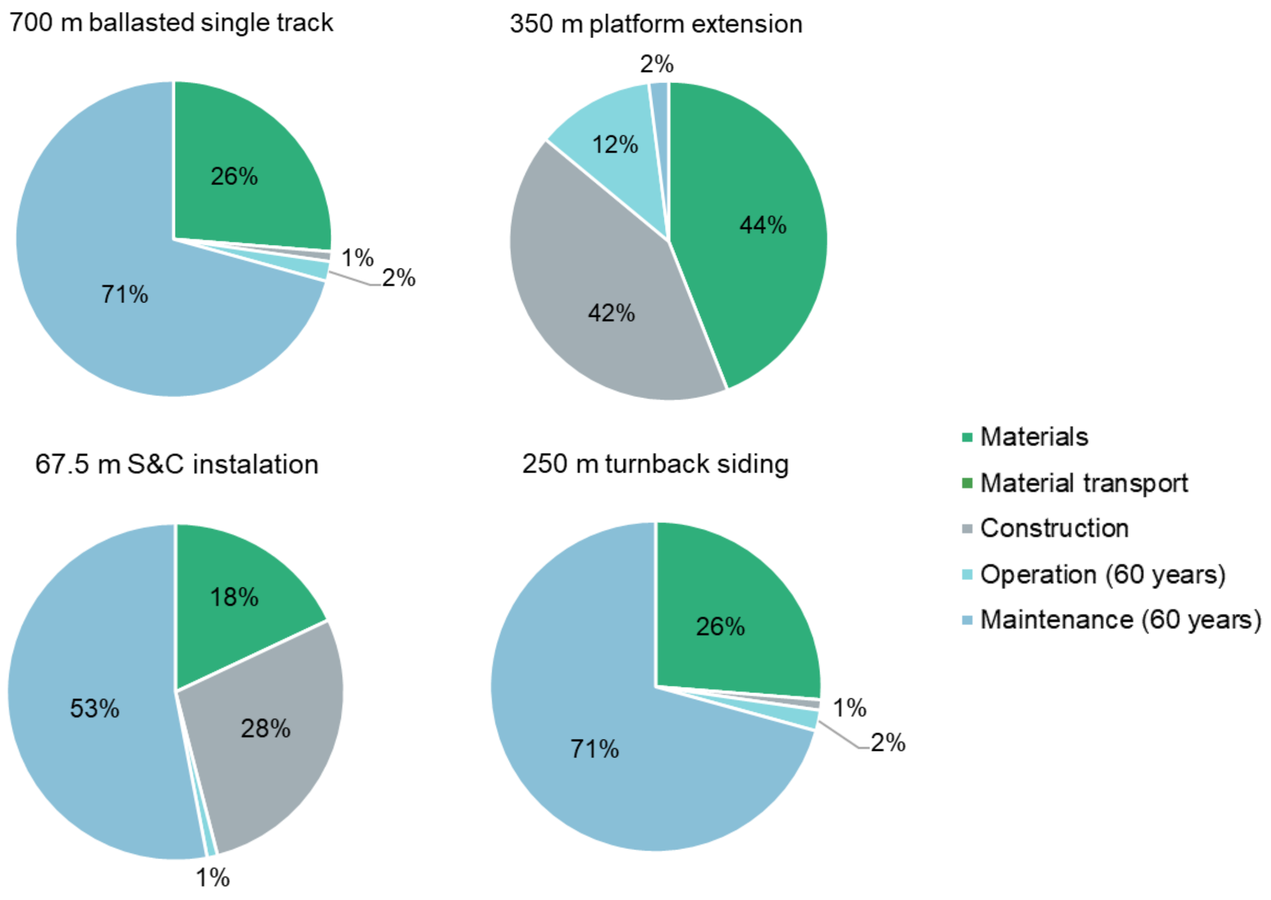


Figure 15: Embodied and operational carbon estimates (as % contribution per component) for the different components of the scheme 249 within rail based case study - Sunderland Station and Sunderland Station track layout improvements

Components within this scheme such as switches and crossings (S&C) installation and operation, platform refurbishment, and its subsequent energy demand for lighting and signalling operations, tend to interact with the national energy grid over the temporal boundary of this analysis. Therefore, in an approach similar to Case 1, the overall operational energy demand of the scheme's components over their 60-year service period is assessed for sensitivity to a decarbonising grid. Changes to the estimated operational emissions where then applied to the whole life carbon estimated of these components to quantify their overall sensitivity to the grid decarbonisation. Under the 'no CCS' setting, the whole life carbon estimates for operation and the maintenance of the new tracks (including S&C), between 2030 and 2060, dropped by only about 8.8-12.4% under the 'Steady Progression' pathway and by about 10-15% under the 'System Transformation' pathway, relative to their 2020 baseline (Figure 16). Assuming the embodied carbon remains constant, grid decarbonisation will influence the whole life carbon of all the assets in this scheme to vary between 3,666 and 3,580 tCO_2eq between 2030 and 2060, under the 'no CCS-Steady Progression' pathway.

Under the 'CCS' setting, which corresponds to the change in the 'System Transformation' scenario only, these carbon savings almost doubled for the 2060 scenario (17-27% savings achieved), relative to the 2020 baseline (Figure 17). Though this scenario is highly unlikely, the purpose of its estimation is to get an insight into the most optimistic savings threshold obtainable from the grid-decarbonisation.

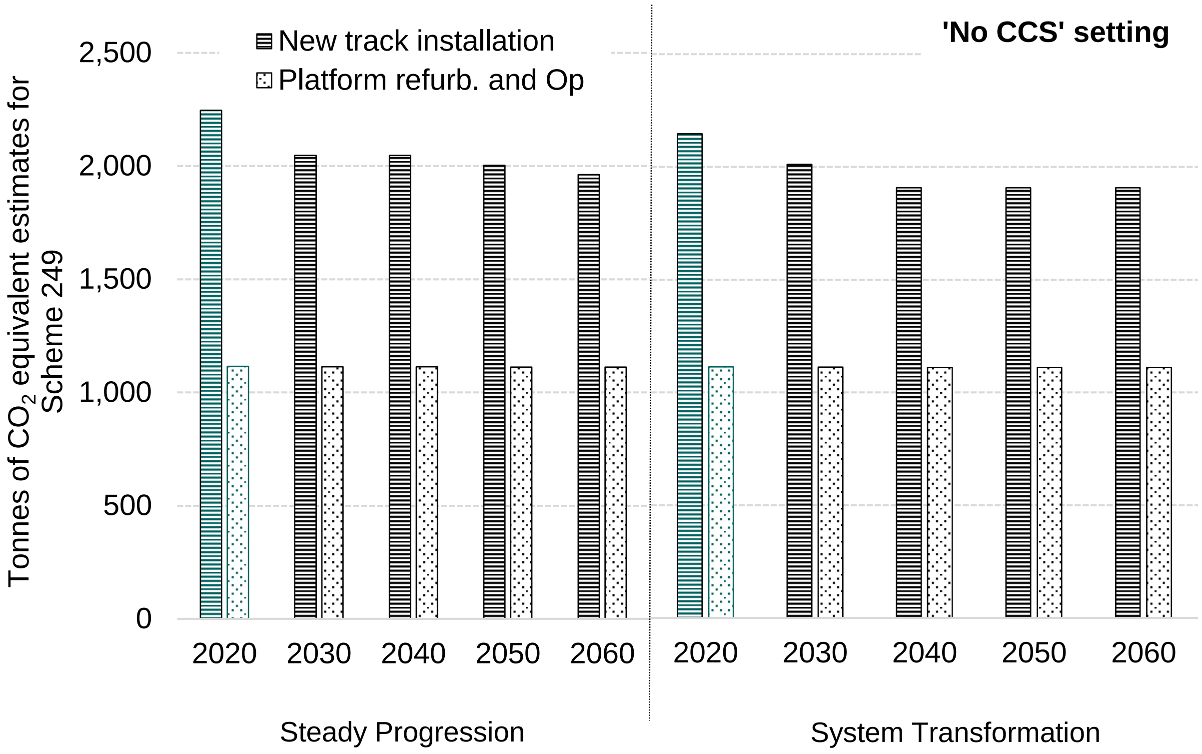


Figure 16: Whole life emissions estimated for scheme 249, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'No CCS' setting

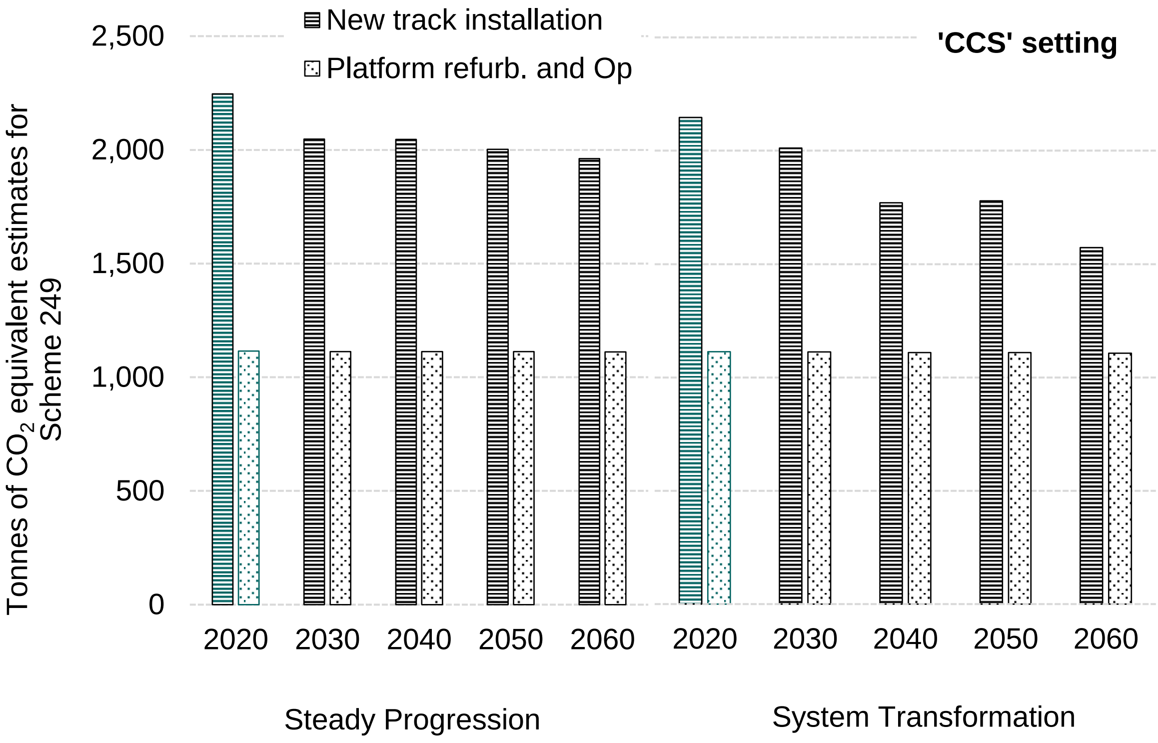


Figure 17: Whole life emissions estimated for scheme 249, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a ''CCS' setting

The whole life carbon for the rail stations and extended platforms hardly seems to respond to any grid decarbonisation measures and this is due to the amount of carbon from the construction materials and the construction itself, being more significant than the energy required to operate the stations.

A hypothetical analysis involving the installation of solar PV systems to not only supply sustainable clean energy to the station operation, but also to the national grid, was integrated into this case study. We assumed installation of 63.5 kWp solar PV panels on the roof of the extended platforms. Such an installation could deliver almost 5 MWh of clean energy annually which, while fully sustaining the station's operational energy demand, also delivers significant amounts of energy back to the grid. These carbon savings amounted to almost 1056 tCO_2eq which has the potential to pay-off the embodied carbon of the installed PV modules. The potential for carbon savings observed here are relatively high since Sunderland Station is undergoing a development which is relatively smaller (platform extension), and thus, is less energy-intensive, as opposed to Scheme 92: Newcastle Airport station (platform and station extension).

Care must be taken with the outcomes reported in this analysis since the uncertainties from real-world specifications, including changing trends in station patronage (and thus electricity consumption patterns), asset maintenance routines, end-of-life management of recovered materials, materialisation of the FES2020 vision, the true installation potential (in terms of capacity), energy conversion efficiency (influenced by the technical characteristics such as geometry and inclination of location, influence of local weather conditions) all have a bearing on the outcomes reported for both the benchmark and the case studies. Therefore, the carbon savings estimated here are mainly for guidance purposes based on assumptions made within the constructs and 'cut-off-criteria' of this system boundary, and must be treated with care prior to practical application and analysis.

References

1. Britpave.org,uk, 2021. What is Slab Track? - Britpave [WWW Document]. URL https://www.britpave.org.uk/RailWhatIsIt.ink (accessed 11.1.21).

2. Circular Ecology UK, 2021. Solar PV Embodied Carbon. Circular Ecology. URL https://circularecology.com/solar-pv-embodied-carbon.html (accessed 7.23.21).

3. Coleman, I., Cornish, A., 2010. Predicting the future for switches and crossings [WWW Document]. Global Railway Review. URL https://www.globalrailwayreview.com/article/6772/predicting-the-future-for-switches-and-crossings/ (accessed 8.4.21).

4. Committee on Climate Change, 2020. The sixth cabron budget: The UK’s path to net-zero. UK.

5. DEMİROĞLU, n.d. Natural Fiber Reinforced polyurethane Rigid Foam.

6. Department for Business, Energy and Industrial Strategy, 2021a. Greenhouse gas reporting: conversion factors 2020 [WWW Document]. GOV.UK. URL https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020 (accessed 8.22.21).

7. Department for Business, Energy and Industrial Strategy, 2021b. Energy consumption in the UK 2020 [WWW Document]. GOV.UK. URL https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2020 (accessed 11.1.21).

8. Department for Transport, 2019. Journey time statistics: data tables (JTS) [WWW Document]. GOV.UK. URL https://www.gov.uk/government/statistical-data-sets/journey-time-statistics-data-tables-jts (accessed 11.3.20).

9. Dolci, G., Rigamonti, L., Grosso, M., 2020. Potential for improving the environmental performance of railway sleepers with an outer shell made of recycled materials. Transportation Research Interdisciplinary Perspectives 6, 100160. https://doi.org/10.1016/j.trip.2020.100160

10. Eerenbeemt, J.V., 2021. Embodied carbon, the hidden emission in infrastructure. distnc. URL https://medium.com/distnc/embodied-carbon-the-hidden-emission-in-infrastructure-b49f3a9dba67 (accessed 10.4.21).

11. Ferdous, W., Manalo, A., AlAjarmeh, O., Mohammed, A.A., Salih, C., Yu, P., Mehrinejad Khotbehsara, M., Schubel, P., 2021. Static behaviour of glass fibre reinforced novel composite sleepers for mainline railway track. Engineering Structures 229, 111627. https://doi.org/10.1016/j.engstruct.2020.111627

12. Ferdous, W., Manalo, A., Van Erp, G., Aravinthan, T., Kaewunruen, S., Remennikov, A., 2015a. Composite railway sleepers – Recent developments, challenges and future prospects. Composite Structures 134, 158–168. https://doi.org/10.1016/j.compstruct.2015.08.058

13. Ferdous, W., Manalo, A., Van Erp, G., Aravinthan, T., Kaewunruen, S., Remennikov, A., 2015b. Composite railway sleepers – Recent developments, challenges and future prospects. Composite Structures 134, 158–168. https://doi.org/10.1016/j.compstruct.2015.08.058

14. Finnegan, S., Jones, C., Sharples, S., 2018. The embodied CO2e of sustainable energy technologies used in buildings: A review article. Energy and Buildings 181, 50–61. https://doi.org/10.1016/j.enbuild.2018.09.037
15. GeoGreenPower.co.uk, 2021. Commercial Solar Panels UK - PV Panels. Geo Green Power. URL https://www.geogreenpower.com/solar-panels/commercial/ (accessed 11.23.21).
16. Gholamali, S., Xiao, Y.C., Tien-Binh, N., Denis, R., 2019. Polyurethane Foams Reinforced with Biobased Materials: Properties and Applications. Current Applied Polymer Science 3, 14–29.
17. Greenhouse Gas Protocol, 2021. Bath Inventory of Carbon and Energy (ICE) | Greenhouse Gas Protocol [WWW Document]. URL https://ghgprotocol.org/Third-Party-Databases/Bath-ICE (accessed 8.22.21).
18. Greenmatch, 2020. How Efficient Are Solar Panels in 2021? [WWW Document]. URL https://www.greenmatch.co.uk/blog/2014/11/how-efficient-are-solar-panels (accessed 7.26.21).
19. Greenspec, 2021. GreenSpec: Environmental Impacts of Rainwater Goods Materials [WWW Document]. URL http://www.greenspec.co.uk/building-design/rainwater-goods/ (accessed 9.24.21).
20. Hammond, G.P., Harajli, H.A., Jones, C.I., Winnett, A.B., 2012. Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations. Energy Policy, Strategic Choices for Renewable Energy Investment 40, 219–230. https://doi.org/10.1016/j.enpol.2011.09.048
21. Hill, N., Brannigan, C., Wynn, D., Milnes, R., van Essen, H., den Boer, E., et al., 2012. The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions. Task 2 paper produced as part of a contract between European Commission Directorate-General Climate Action and AEA Technology plc. UK.
22. Kaewunruen, S., Liao, P., 2021. Sustainability and recyclability of composite materials for railway turnout systems. Journal of Cleaner Production 285, 124890. https://doi.org/10.1016/j.jclepro.2020.124890
23. Kiani, M., Parry, T., Ceney, H., 2008. Environmental life-cycle assessment of railway track beds. Proceedings of the Institution of Civil Engineers - Engineering Sustainability 161, 135–142. https://doi.org/10.1680/ensu.2008.161.2.135
24. Koller, G., 2015. FFU synthetic sleeper – Projects in Europe. Construction and Building Materials, Railway Engineering-2013 92, 43–50. https://doi.org/10.1016/j.conbuildmat.2015.03.118
25. Kuranchie, C., Yaya, A., Bensah, Y.D., 2021. The effect of natural fibre reinforcement on polyurethane composite foams – A review. Scientific African 11, e00722. https://doi.org/10.1016/j.sciaf.2021.e00722
26. Louwen, A., van Sark, W.G.J.H.M., Faaij, A.P.C., Schropp, R.E.I., 2016. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. Nat Commun 7, 13728. https://doi.org/10.1038/ncomms13728
27. Lu, G., Liu, P., Wang, Y., Faßbender, S., Wang, D., Oeser, M., 2019. Development of a sustainable pervious pavement material using recycled ceramic aggregate and bio-based

polyurethane binder. Journal of Cleaner Production 220, 1052–1060. https://doi.org/10.1016/j.jclepro.2019.02.184

28. Merchan, A.L., Belboom, S., Léonard, A., 2020. Life cycle assessment of rail freight transport in Belgium. Clean Techn Environ Policy 22, 1109–1131. https://doi.org/10.1007/s10098-020-01853-8
29. National Grid, 2020. National Grid's Net Zero Commitment [WWW Document]. URL https://www.nationalgrid.com/stories/journey-to-net-zero/national-grids-net-zero-commitment (accessed 7.2.21).
30. National Grid ESO, 2020. Future Energy Scenarios. National Grid ESO, UK. https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents
31. Network Rail, 2021a. Capital Carbon: Guidance note [Environment].
32. Network Rail, 2021b. Railway Recycling - Sleepers. URL https://railwayrecycling.co.uk/how-we-work
33. Network Rail, 2021c. Material specifications for Overhead Line Equipment.
34. Network rail, 2021. Procurement [WWW Document]. Network Rail. URL https://www.networkrail.co.uk/industry-and-commercial/supply-chain/procurement/ (accessed 11.1.21).
35. Network Rail, 2021d. Beyond wood – first recycled plastic railway sleepers laid on Network Rail tracks [WWW Document]. Network Rail Media Centre. URL https://www.networkrailmediacentre.co.uk/news/beyond-wood-first-recycled-plastic-railway-sleepers-laid-on-network-rail-tracks (accessed 7.23.21).
36. Network Rail, 2021e. Network Rail Environmental Sustainability Strategy 2020-2050. Network Rail, London, UK.
37. Network Rail, 2019. Pioneering trial for solar-powered trains [WWW Document]. Network Rail. URL https://www.networkrail.co.uk/stories/pioneering-trial-for-solar-powered-trains/ (accessed 7.23.21).
38. Network Rail, 2018a. Sleepers » Railway Recycling. Railway Recycling. URL https://railwayrecycling.co.uk/railway-sleepers/ (accessed 10.25.21).
39. Network Rail, 2018b. Developing a greener railway [WWW Document]. Network Rail. URL https://www.networkrail.co.uk/stories/developing-a-greener-railway/ (accessed 8.2.21).
40. Network Rail, 2015. Network Rail - a guide to Overhead Electrification.
41. Newcastle International, 2021. Airport Masterplan 2035 UPDATED 2019 LR_ [WWW Document]. URL https://online.flowpaper.com/7aaf0769/AirportMasterplan2035UPDATED2019LR/ (accessed 12.2.21).
42. Office of National Statistics, 2020. Region and Rural-Urban Classification [WWW Document]. GOV.UK. URL https://www.gov.uk/government/statistical-data-sets/nts99-travel-by-region-and-area-type-of-residence (accessed 12.1.21).
43. Office of Rail and Road, 2021. Estimates of station usage | ORR Data Portal [WWW Document]. URL https://dataportal.orr.gov.uk/statistics/usage/estimates-of-station-usage (accessed 11.1.21).

44. Office of Rail and Road, 2020. Rail infrastructure and assets. Office of National Statistics, UK.

45. Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E.G., Luderer, G., 2017. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nat Energy 2, 939–945. https://doi.org/10.1038/s41560-017-0032-9

46. Pons, J.J., Villalba Sanchis, I., Insa Franco, R., Yepes, V., 2020. Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks. Environmental Impact Assessment Review 85, 106444. https://doi.org/10.1016/j.eiar.2020.106444

47. Rail Transport Decarbonisation Taskforce, 2019. Decarbonisation – our final report to the Rail Minister [WWW Document]. URL https://www.rssb.co.uk/sustainability/decarbonisation/decarbonisation-our-final-report-to-the-rail-minister (accessed 9.3.21).

48. RailUK, 2020. Slab Track - Paving the P-Way. Rail UK. URL https://railuk.com/general-interest/slab track-paving-the-p-way/ (accessed 11.1.21).

49. Rempelos, G., Preston, J., Blainey, S., 2020. A carbon footprint analysis of railway sleepers in the United Kingdom. Transportation Research Part D: Transport and Environment 81, 102285. https://doi.org/10.1016/j.trd.2020.102285

50. RSSB, 2021. Rail Carbon Tool [WWW Document]. URL https://www.rssb.co.uk/sustainability/rail-carbon-tool (accessed 10.8.21).

51. Salih, C., Manalo, A., Ferdous, W., Yu, P., Abousnina, R., Heyer, T., Schubel, P., 2021. Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast. Case Studies in Construction Materials 15, e00597. https://doi.org/10.1016/j.cscm.2021.e00597

52. Sekisui Railway Technology, 2021. FFU synthetic wood [WWW Document]. URL https://www.sekisui-rail.com/en/technology.html (accessed 7.28.21).

53. Sengsri, P., Ngamkhanong, C., Melo, A.L.O. de, Papaelias, M., Kaewunruen, S., 2020. Damage Detection in Fiber-Reinforced Foamed Urethane Composite Railway Bearers Using Acoustic Emissions. Infrastructures 5, 50. https://doi.org/10.3390/infrastructures5060050

54. Stripple, H., 2001. Life Cycle Assessment of Road: A pilot study for inventory analysis. IVL Swedish Environmental Research Institute Ltd, Sweden.

55. Sunderland City Council, 2020. Sunderland city data [WWW Document]. Sunderland City Council. URL https://www.sunderland.gov.uk/article/13270/Sunderland-city-data (accessed 12.2.21).

56. Temple- ERM, 2013. High Speed Rail: Consultation on the route from the West Midlands to Manchester, Leeds and beyond Sustainability Statement: Appendix E11 – Material Use.

57. Transport for the North, 2021a. Draft Decarbonisation Strategy for Consultation. Transport for the North. URL https://transportforthenorth.com/reports/tfn-draft-decarbonisation-strategy-for-consultation-june-2021/ (accessed 10.25.21).

58. Transport for the North, 2021b. Transport for the North: Regional Vehicle Statistics: Personal communication.

59. Transport for the North, 2020. Future Travel Scenarios: Adaptive planning to deliver our strategic vision in an uncertain future. Transport for the North.
60. Uglešić, I., Mandić, M., Milardić, V., 2009. Design and testing of 25 kV 50 Hz traction power system. Modern electric traction: power supply 3–13.
61. Yu, P., Manalo, A., Ferdous, W., Abousnina, R., Salih, C., Heyer, T., Schubel, P., 2021. Investigation on the physical, mechanical and microstructural properties of epoxy polymer matrix with crumb rubber and short fibres for composite railway sleepers. Construction and Building Materials 295, 123700. https://doi.org/10.1016/j.conbuildmat.2021.123700

Appendix

Composition of the low-carbon sleepers assumed in section 0

Sleeper type	Materials	kg per sleeper
Recycled Concrete Sleeper	Concrete	117.8
	Aggregate	166.7
	Steel - Rebar - Recycled	14.2
	Plastic - Recycled	33.7
FFU sleeper	Polyurethane - Rigid foam	5
	Fibreglass (Glass wool)	300
Steel Sleeper	Steel (@30% recycled content)	87.5

Table 10: Material specifications for the low-carbon alternative sleepers adopted for the sensitivity study of rail-carbon estimation

Additional data on the steadily decarbonising energy grid and related carbon intensity used in the operational carbon estimation and analysis of the road and rail infrastructure

Materials and parameters	**Embedded energy**	**Unit**
Rail pads	3,080	each
Fastening (toe insulator)	6,160	each
Fastening (clips)	6,160	each
Rail pads	20	GJ/tonne
Fastening clips	20	GJ/tonne
Reinforcement bars	18	GJ/tonne
Concrete	5.6	GJ/tonne
Aluminium	223	GJ/tonne
Ballast	0.1	GJ/tonne
Copper	17.5	GJ/tonne
Terrazzo tiles	1.4	GJ/tonne
1kmtrack_concrete	366	tonnes
1kmtrack_pads	1.54	tonnes
1kmtrack_fastening	12.3	tonnes
1kmtrack_reinforcement bar	2.3	tonnes
1kmtrack_rail track	56	tonnes
1kmtrack_ballast	4,367	tonnes
1kmtrack_sleepers	451	tonnes
Source: Greenhouse Gas Protocol, 2021; Greenspec, 2021; Kaewunruen and Liao, 2021; Kiani et al., 2008; Network Rail, 2021		

Table 11: Embodied energy within the materials commonly used for the construction, operation and maintenance of the assets in the rail infrastructure

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