MEASURING ROAD INFRASTRUCTURE CARBON:

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

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February 2022

DOI: https://doi.org/10.48785/100/143

UKRI Engineering and Physical Sciences Research Council

DecarboN8

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Acknowledgements

DecarboN8 has received funding from the EPSRC Energy Programme, grant agreement EP/S032002/1.

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.

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

This report should be cited as:

Lokesh, K., Densley-Tingley, D. and Marsden, G. (2022) Measuring Road Infrastructure Carbon: A ‘critical’ in transport’s journey to net-zero. Leeds: DecarboN8 Research Network. DOI: https://doi.org/10.48785/100/143

Glossary

BECCS	Bioenergy with carbon capture and storage
Capital carbon	The embodied carbon plus the emissions from external sources including material and energy use by mobile plant and equipment, site utilities, personnel transport to site etc
Carbon intensity	The carbon dioxide emissions related to electricity generation, including emissions from large, metered power stations interconnector imports, transmission and distribution losses. This also accounts for national electricity demand, embedded wind and solar generation (source: carbonintensity.org.uk)
CCS setting	An optimistic setting used in the sensitivity analysis of this study in which the negative carbon derived mainly from 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 in which there are significant societal changes, higher levels of energy efficiency, and lower energy demand.
Cut-off criteria	Used in the system boundary to highlight materials or any particular stages that may be excluded from the analysis
DACCS	Direct Air with carbon capture and storage
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

KWh	Kilowatt hour
Leading the Way pathway	Scenario from FES2020, the fastest route to decarbonisation in which 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
MWh	Megawatt hour
National Highways Carbon Tool	A free to use spreadsheet-based carbon tool used for calculating and reporting construction, operation and maintenance carbon on behalf of National Highways (previously Highways England)
No CCS setting	A setting used in the sensitivity analysis of this study in which 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)
Operational carbon	The carbon dioxide emissions associated with the operation and maintenance of a built asset, across its whole life cycle
Post-opening Project Evaluation (POPE)	An independent 'meta' report that is published upon evaluating a functioning capital project (for example, new-road, bypass construction or lane extensions) at 1 year and 5 years after completion
Secondary material	Materials extracted from the waste streams from the whole life cycle of the road's infrastructure, which are often reused or treated and repurposed
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 in which the initiative lies with the integration of innovation at the supply side
TCO_2eq	Tonnes of carbon dioxide equivalent

Executive Summary

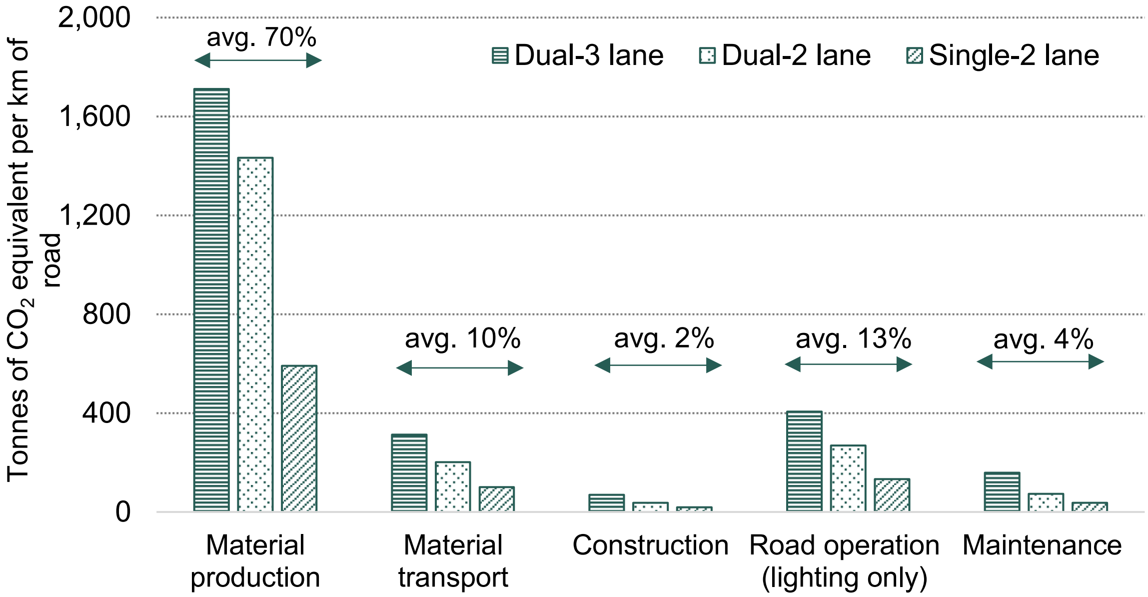
The Department for Transport's Decarbonisation Plan focuses on 'tailpipe emissions' from vehicles. Whilst the plan acknowledges embodied emissions in the construction and management of infrastructure and the building of new vehicles, no clear indications of the scale of these emissions nor their significance have been provided. The national accounting responsibility for those embodied emissions sits with the Department for Business, Energy and Industrial Strategy (BEIS) at a national scale. 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 promoting new infrastructure, such as Transport for the North (TfN), is that they will need to present a 'whole-life' approach which deals with all of 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, the departments currently offer 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 the roads transport infrastructure to inform decision-making.

Summary of Main Findings

The whole life carbon (WLC) impacts of some of the key components of the road transport infrastructure (construction of a new road, lighting operation and maintenance of the built asset) were estimated employing life cycle assessment, over an assumed service life of 40 years. Please see S_Figure 1.



S_Figure 1: Life cycle carbon emissions associated with different scales of asphalt pavement construction

- The whole life carbon of 1 km of road, modelled within the boundary constructs and the assumptions adopted in this study is determined to be 2,658.9 tCO2eq for dual-3 lane; 2,014.1 tCO2eq for dual-2 lane; and 880.3 tCO2eq for single-2 lane carriageway.
- The ‘Material production’ phase is determined to be the dominant carbon contributor across the whole life of a road.
- The key embodied carbon contributors are the energy-intensive materials, concrete and asphalt.
- The surface layer of the asphalt pavement (road) is the most energy intense (5 TJ over the asset’s assumed service life of 40 years), followed by the embodied energy of the sub-grade layer (4.2 TJ).
- Material-related emissions are closely followed by those attributed to material transport energy needs and thus electricity production and supply. Road-lighting operation is the next highest carbon contributing sub-system in the whole life cycle of a new road, responsible for 12-15% of the asset’s whole life carbon.

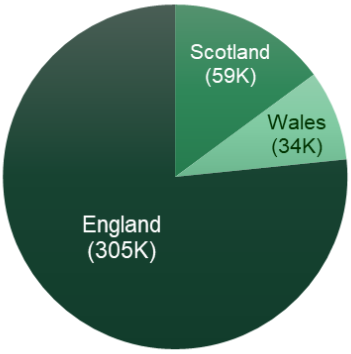
Sensitivities to inter-sectoral interactions

- Use of low-carbon alternatives and secondary (reclaimed) materials could reduce the whole life carbon of new roads by 2-12% over the asset’s life period of 40 years (2020-2060).
- A decarbonising energy grid could reduce the whole life carbon of new roads by 8-42% over the asset’s life period between 2030 and 2060, relative to the 2020 estimates. The level of savings is dependent on the certainty to which the grid decarbonisation occurs, including the technological integration, maturity and the level of societal behavioural change assumed within the FES 2020 scenarios.
- In the assessment of a hypothetical scenario, in which an optimistic grid decarbonisation pathway (System Transformation) is applied across the whole life of the built assets, with access to negative carbon (‘CCS’ setting), 10-30% of whole life carbon remains a challenge to achieving carbon neutrality even in the long-run. One of the main contributors of this ‘stubborn’ remainder of whole life carbon is the embodied carbon in the materials.

ROAD INFRASTRUCTURE CARBON ASSESSMENT

1 Road infrastructure – an introduction

Roads play an integral part in a nation’s infrastructure by enabling safe and reliable distribution of resources to the corners of the nation. The UK’s road network is made of major roads, minor roads, and private roads in the urban and rural areas, spanning about 400,000 km across the nation. Distribution of the various road types and lengths in *km* has been presented in Figure 1. This road network catered to about 340 billion vehicle miles in 2019 which dropped to about 115 billion vehicle miles in 2020, as a result of travel restrictions related to the management of the Covid-19 pandemic (Department for Transport, 2021).



Country	Motorways	Rural 'A' roads	Urban 'A' roads	Minor rural roads	Minor urban roads	Total
England	3,117	23,427	9,484	152,941	116,266	305,234
Wales	142	3,705	530	22,662	6,813	33,851
Scotland	476	9,001	1,365	32,726	15,706	59,274

Figure 1: Great Britain’s total road length (km) and the distribution of different types of roads (Department for Transport, 2019).

Road building and maintenance depend on the extraction of non-renewable resources (construction materials and thermal/mechanical energy), in addition to the direct and indirect costs to the environmental and natural capital that this infrastructure incurs, including disruptions to biodiversity and the unintended damage to heritage sites (Sloman et al., 2017).

The pathways to decarbonisation are complex but all involve a rapid shift to electrification for cars and either a hydrogen or battery solution for heavier vehicles in due course. However, decarbonisation of the tailpipe of the vehicle is only one part of the decarbonisation challenge. The energy sources used for propulsion need to be decarbonised, as do the maintenance and operation of the infrastructure they run on. Because of this, the production process of the vehicles and the costs of any new infrastructure built to accommodate forecast growth in travel demand needs to be considered (Hill et al., 2020).

The Department for Transport predominantly takes responsibility for reducing tailpipe emissions, although it recognises that vehicle construction, road construction, and associated operational electricity emissions are important. However, as the arbiter of a multi-billion-pound annual infrastructure budget, the department’s lack of acknowledgement of the relative scale of the importance of construction emissions is problematic. Organisations, such as Transport for the North (TfN), who are promoting new infrastructure schemes are, rightly, being held to account for the total carbon implications of the schemes. It is often argued, for example, that road widening will help reduce congestion, smoothing flows and cutting emissions from stop-start traffic. However, it is currently difficult to assess whether, and if so, over how many years, any savings from smoother flow would offset the emissions associated with construction or any induced traffic. This paper aims to quantify the capital and operational carbon of road infrastructure components to both highlight the significance of infrastructure carbon and to emphasise their importance in decision-making in transport.

1.1 Infrastructure Carbon Assessment

Embodied carbon refers to the carbon dioxide and its greenhouse gas equivalents (CO_2eq) that are released over the life of a product or a piece of infrastructure. The life stages, within the system boundary, include extraction of raw materials, pre-processing, transporting them between facilities and the construction site, use, maintenance and, finally disposal or reuse.

National Highways (formerly Highways England) employs its own guidance for environmental impact assessment to appraise and approve new development schemes (Highways England, 2020). In accordance to the environmental impact appraisal followed by National Highways, which is also aligned with the principles of life cycle assessment (LCA) (International Organisation of Standardisation, 2018) the goal, scope and functional unit of this study first have to be established. After establishing the construction, operation and maintenance GHG emissions, the HE guidance recommends a carbon impact assessment post-completion. This carbon impact assessment is restricted to the time of construction and with a follow-up for a specific period after the project completion (one year after and five years after the completion). This report is called Post-Opening Project Evaluation or POPE. In this study, to assess the whole life carbon impacts of our selected road schemes, we will be employing LCA methods recommended within the ISO14040 and the ISO14044 (International organisation of Standardisation, 2018), coherent with the HE guidance. The material and energy flows through the life cycle stages, from within the scope of our analysis, will be quantified and disaggregated by the sub-systems and by the layers of the pavement for an in-depth analysis.

The ISO guidance for life cycle assessment requires us to set a functional unit (F.U.) to help enable the comparison of construction scales and/or different scenarios that have been planned for further study. Then, the scope of study is to be established following the guidance provided for road schemes in Highway England’s ‘LA114 Climate’ document. This will be followed by an impact assessment employing methods suggested within the ISO standards for life cycle assessment, interpreting and discussing the quantified outcomes of this analysis. This will be a general approach applied for both within the road transport system assessment. In this hybrid approach, we will be utilising the National Highways Carbon Tool for estimating carbon impacts from material supply, transport and pavement construction using its built-in carbon factor inventories and flexibility to add custom carbon factors suitable for the secondary materials that are planned for and evaluated within the sensitivity study.

1.2 Scope of Study

To assess the whole life carbon impacts of the road infrastructure components, this paper has adopted the principles of life cycle assessment (LCA), recommended within the ISO14040 and the ISO14044 (International Organisation for Standardization, 2018). In contemporary LCA, setting a functional unit enables the comparative environmental evaluation of two or more product systems. This study, however, is exploratory in nature and aims to understand the basic carbon expenditures associated with major road development schemes, over their lifetime. Each road is unique. Making an assessment of the embodied emissions of a 'typical road' is much more difficult than commonly analysed components such as steel sections or a particular car model, where each unit is identical Defining the scope of this analysis is likely to be more challenging owing to the practicalities involved in the construction of road networks, particularly the lifetime of such systems, which tend to be many decades. For the purpose of this study, the functional unit is set as 1 km of an asphalt road with an assumed life-period of 40 years, in line with the assumptions adopted in the published literature (Milachowski et al., 2018; Stripple, 2001). This is undertaken for single-2 lane, dual-2 lane and dual-3 lane carriageway that are respectively 3.6 m, 7.2 m and 11 m wide each way. The rationale for the choice of this time period is that almost all of the materials are subject to renewal every 10-20 years, particularly in the surface layers. The binder layers of the asphalt pavement tend to be completely replaced every 40 years. The systems and the sub-systems that fall within the scope of this analysis, as shown by the area within the dashed line in Figure 2, include material production, material transport, construction, road operation (lighting only) and maintenance. Whole life carbon ideally corresponds to the embodied and operational carbon, in addition to that which is released from demolition and disposal. The final sub-system which corresponds to the disposal phase, 'road decommissioning', rarely occurs for the asset in question. As a result, this sub-system has been excluded from this analysis. 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 those from vehicular emissions which arise from consumption by users (user emissions).

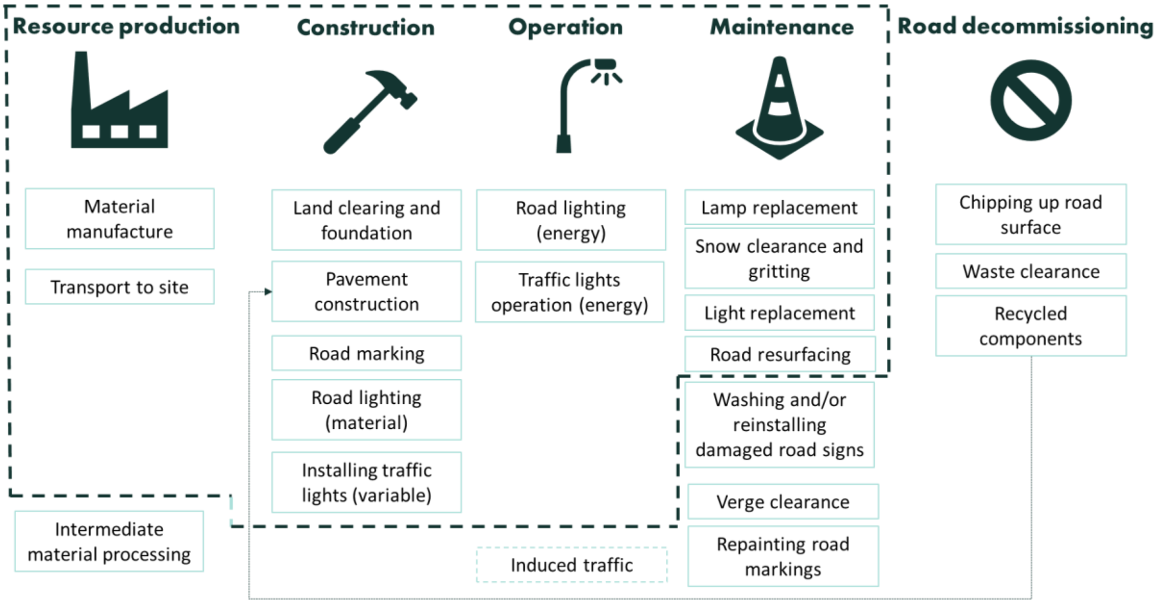


Figure 2: A breakdown of the systems and sub-systems embedded in an asphalt pavement, representing the system boundary of this study (Dashed lines show those sub-systems and processes that are within the scope of study)

The goals of this analysis were:

- To quantify the embodied carbon of the materials and energy flows through the systems involving asphalt road building, operation (lighting only) and maintenance of the infrastructure over the time period of 40 years.
- To explore the impact of technology uptake, in terms of use of low-carbon alternative construction materials, on the overall embodied carbon of the infrastructure in question
- To understand how the steadily decarbonising electricity grid will impact on carbon emissions associated with relevant elements of the road infrastructure's sub-systems

2 Impact assessment methodology

Road construction, at present, is a resource-intense phase within road network management. Conventionally, from an LCA viewpoint, an environmental focus must include multiple environmental indicators including resource depletion, stemming from a significant use of non-renewable resources, respiratory inorganics from the release of volatile components during the 'hot-method' asphalt preparation and potential ecotoxicity from the leaching of toxic substances and particulates from the lower course of the pavement (especially if any secondary materials that have been treated for performance are used). However, the emphasis of this study is on the embodied carbon of the asphalt pavement, therefore, carbon impact will be the only environmental indicator adopted.

The material and the energy flows are quantified and estimated for use in the National Highways Carbon Tool [1]. The National Highways Carbon Tool utilises a dedicated emission factor database, Inventory of Carbon and Energy (ICE) v2. The energy, waste, and transport emissions factors are adopted from the UK Government emission conversion factors for greenhouse gas reporting 2020 (Department for Environment, Food and Rural affairs, 2019). The emissions from the extraction and processing of the raw materials have also been included within the carbon factors. However, this does not include emissions related to processing these raw materials into that suitable for construction and transportation to the construction site. Therefore, these specific emissions are estimated separately for each of the components and then factored into the final accounting. The embodied and operational carbon emissions are estimated in tonnes of carbon dioxide equivalents using the approach presented below:

GHG emission (tCO_2eq) = material and energy flow × emission factors

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* (kilowatt hours) for electricity consumed. Each of the sub-systems in the 'asphalt-pavement' system have been discussed in the upcoming sections detailing further the technical data and relevant assumptions adopted for this analysis.

2.1 Core study - Description of sub-system and processes

Resource production and transport

Primary resources in asphalt pavement are those that are required for the asphalt mixture. This includes bitumen binder, coarse and fine natural aggregates, and binders. Additives that alter the binder characteristics, at the refinery and during transportation to the construction site such as stabilisers and crumb rubbers, fibres, and, prior to application, rejuvenators are also used for the mixture preparation. The chosen approach for asphalt pavement ('hot' mix method adopted for this study) and the quality of the binder production influences the overall energy intensity, which in turn impacts the embodied carbon content of the mixture used. In this study, we are using the carbon factors recommended for the asphalt mixtures by DEFRA (Department for Business, Energy and Industrial Strategy, 2021) and within the National Highways Carbon Tool.

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[1] The National Highways Carbon Tool is a spreadsheet-based carbon calculator dedicated to quantifying the construction and maintenance emissions from activities undertaken on behalf of National Highways (formerly Highways England)

Material Transport

Measuring fuel as *litres* and energy as *kWh* supplied, energy consumption is captured while clearly distinguishing each of the fuel types for both constructions, and more specifically by fuel-type, for heavy machinery and material transport operation. The assumed transport distance for the various materials is assumed to be 100-150 km from the construction site. Diesel consumption of the heavy good vehicles varies with the type and capacity of the load transported between the facilities and the construction site. For our analysis, it is assumed that at full-load and empty load, a truck carrying 100 tonnes of natural aggregates would consume 39 L and 30 L per 100 km travelled and that carrying 50 tonnes of asphalt mix would consume 38 L and 30 L, respectively similar to that assumed in the open literature (Milachowski et al., 2018; Stripple, 2001; Wang et al., 2021).

Asphalt pavement construction

Data on material and energy flows and highway design considerations for the asphalt pavement were based on published scientific industrial literature and the UK highway pavement guidance published by the National Highways (Greenhouse Gas Protocol, 2021; Hasan et al., 2020; Kent County Council, 2000; Milachowski et al., 2018). This phase begins with site preparation involving clearing of vegetation, earth moving and reinforcing the foundations, in preparation for the pavement. The foundation of the pavement is either lime or concrete stabilised. In some cases, a blend of fly-ash from municipal waste incineration plants or ground granulated blast furnace slag, are used as relatively environmentally benign alternatives. The requirement, and thus, the composition of the pavement layers vary with the soil type and the extremity of local weather conditions.

The road structure is made for four distinct layers which include the surface layer, asphalt binder, sub-base, and the sub-grade layer as presented in Figure 3.

Sub-grade

The sub-grade layer is made of standard quality compacted soil and is either acquired from the land preparation process or imported from other excavation sites. The purpose of this layer is to distribute the load and disperse stress from the base layer and, by standard practice, it requires soil compaction and the addition of other materials that maintain the desired mechanical properties of the soil. In areas of colder weather, a frost blanket or capping layer is added between the sub-base and the sub-grade layers (Kent County Council, 2000). For example, cement can be used to stabilise silty and granular soil thus forming a capping layer. Owing to the stress from the upper layers, the aggregates are subjected to abrasion leading to the formation of fine sediments. To avoid sedimentation and poor drainage, a geo textile layer is generally added between these layers for layer integrity over the pavement’s lifetime.

Sub-base

The sub-base layer is made of granular (coarse and fine) aggregate, free from organic matter, working as a stress-absorbing plate for the asphalt bound base layer. The aggregates used for this layer are similar to that applied to the sub-grade layer.

Base course

The base course is generally constructed with natural aggregates bound to bitumen. Careful preparation of this course is essential as it forms the foundation for the crucial upper layers that interface directly with high levels of stress from vehicles and the environment. The moisture content of this layer should, therefore, be maintained at 4% or lower at the time of application.

Binder course

This is generally built with natural aggregates mixed with polymer-modified asphalt and asphalt emulsion. This layer is subjected to severe loading, and therefore must be constructed to high standards. In some construction practices around the world, cement fillers are used to prevent long-term deformation and better rutting performance. However, the sustainability standards in Europe and the UK suggest reduction and elimination (where possible) of high-impact construction materials.

Surface course

The highest level of stress is experienced by the surface course. This course is prepared from a mixture of asphalt binder which is mixed with high-quality mineral aggregates at very high temperatures to cater to the asphalt's viscosity during the application process. The pavement layer is then coated with bitumen emulsion for ease of maintenance over the life of the pavement. The fuel consumed operating the construction machinery is accounted for through the carbon tool. The key material and energy flows through the system have been presented in Table 1.

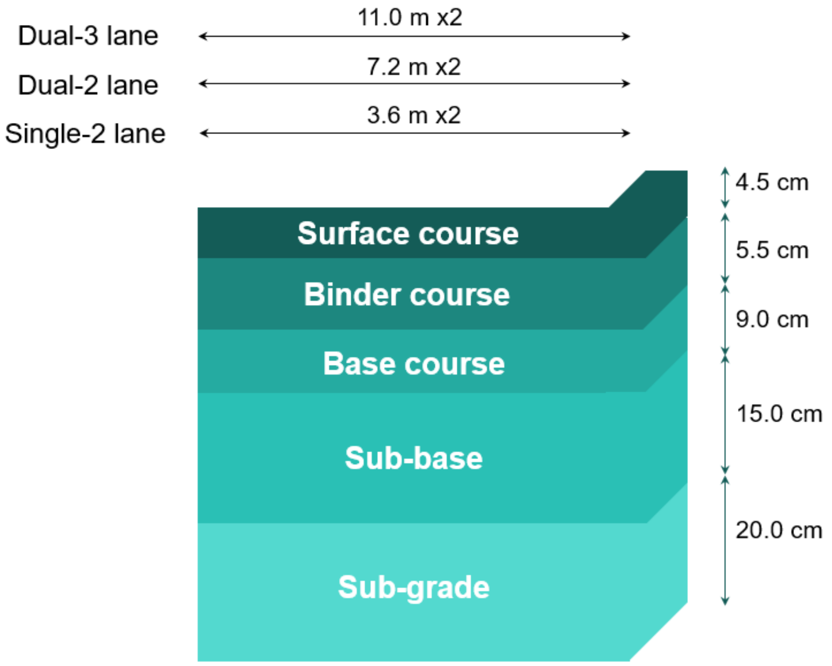

Figure 3: Cross section and the assumed dimensions per layer of asphalt pavement accounted for by the three case studies in this analysis (Kent County Council, 2000).

Road operation and maintenance

Road operation, from an infrastructure perspective, mainly entails road lighting and signal operation, including installation of warning signs, road markers, road signs and other traffic management equipment such as that found on smart motorways. The main energy consuming aspect of road operation is road lighting. Following the assumption in the earlier literature, it is assumed that the 1 km stretch in this study is illuminated by LED road lights for 4,350 hours in a year, accounting for the extended and shortened lighting required over the winter and summer months (Hanson et al., 2012; Milachowski et al., 2018; Stripple, 2001). Maintenance includes regular trimming of the verges, washing of road signs and snow clearing. However, only those procedures that have significant impact on the overall embodied carbon of a road over its lifetime, including fuel and material consumption for salt-gritting (12 times per year on average), patching of the road-surface, and routine road resurfacing (every 5-10 years, depending in the construction quality of the first pavement) (Hanson et al., 2012; Milachowski et al., 2018) have been included in this study. Resurfacing involves milling of the top layers of the road surface. The milled top layers may be collected and treated with rejuvenators for reapplication to the same road or in other road schemes. This method of reuse is less energy intensive but may impact the overall life of the road requiring frequent maintenance procedures. So, adhering to the standard industrial practice, we assume that a new layer of asphalt mix is used in the maintenance procedures.

End of life management (excluded)

Roads that have reached the end of their functional life are either refurbished or decommissioned through road closure. Sometimes, they are milled away to the lower depths to recover the materials invested for reuse in other projects. However, this stage is rarely encountered in the UK's road transport infrastructure. As a result, this stage is left outside the scope of our analysis.

Detailed information on the data types, sources of information and the reference life cycle stages that need to be considered when undertaking embodied emissions and energy evaluations have been presented within the Design Manual for Roads and Bridges, 'LA114 Climate'[2] (Standards for Highways, 2021, p. 114). The resource inventory listed in Table 1, provides a base estimate of material and energy flow through the different life cycle stages of the construction, operation and maintenance (equipment energy and renewal materials required for over 40 years) of 1 km of asphalt pavement.

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[2] This document is dedicated to fulfilling the requirements for assessing and reporting the effects of climate on highways and the impact of construction, operation and maintenance projects (Source: Standards for Highways, 2021)

Phases	Parameters	Sub-parameters	Quantity	Units
Road construction	Asphalt Surface layer	Polymer modified bitumen (surface)	6.75	kg/m^2
(Material production and procurement)	Asphalt surface layer	Polymer modified bitumen (internal)	99.45	kg/m^3
		Aggregate	3,750	kg/m^3
	Asphalt Binder layer	Bitumen emulsion	0.45	kg/m^2
		Aggregate	2925	kg/m^3
		Polymer modified bitumen (internal)	69.8	kg/m^3
	Asphalt base layer	Bitumen	55.05	kg/m^2
		Aggregate	3,523	kg/m^3
	Sub-grade layer	Gravel	2,739	kg/m^3
		Sand	948	kg/m^3
	Diesel		26,000	litres
	Electricity		22.96	TJ
	Concrete	Pre-cast barriers (except for single-2 lane construction)	1000	metres
	Steel	variable		kg
Machinery	Asphalt paver		2	each
	Vibrating roller		4	each
	Bitumen sprayer		5	each
	Tandem roller		1	each
	Fuel consumption		9,529	litres
Operation and Use	Road lighting	Electricity	6.8	TJ
Maintenance	Road resurfacing (every 10 years)	Polymer modified bitumen (surface)	21.24	kg/m^2
	Road gritting and clearance	Sand, salt and aggregate mix	86.2	kg/m^2
	Fuel use	Diesel	3,754,117	litres
	Salt gritting	Sand-Aggregate mix	0.18	kg/m^2

Note:

Materials are measured in tonnes, except where numbers of items, for example, steel columns for lighting, pre-cast concrete barriers have been used. Fuel use during the construction process is measured in litres, while energy use over the life period of the road is measured in kWh and converted to TJ for final reporting.

Source: (Hill et al., 2012; Milachowski et al., 2018; Greenhouse Gas Protocol, 2021; Vega-Araujo et al., 2020)

Table 1: 'Bill of materials' and other specifications for the construction, operation, and maintenance of 1 km asphalt pavement over a service period of 40 years

2.2 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 and numbers of bridges or tunnel sections could all have an impact on the actual figures.

However, our aim is to provide some reasonable approximations that enable this to be deployed. Here is 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 road infrastructure components assumed for both benchmarking and application in the case studies are speculative in nature.
- The ‘bill of materials’ adopted here for the road transport infrastructure construction are restricted to the current scenarios and design specifications in England.
- 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 road network.
- 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 related to the construction sector (for application to the road’s LCA) have been excluded due to lack of data on adaptable or applicable pathways within the scope of this study.
- There is little or no information available on the material procurement specifications and sources. This study has, therefore, made assumptions on the distance between suppliers and 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 would have been valuable considerations. However, these aspects have been excluded due to lack of primary data. Informed assumptions on material circularity (use of secondary resources) based on the evidence available from published industrial and scientific literature have been adopted for the sensitivity study.

2.3 Sensitivity study

Sensitivity to integration of sustainable alternatives

Carbon neutrality by 2050 means that road infrastructure must adopt as many feasible technological solutions as possible to reduce or eliminate the embodied carbon in its building materials. In this section we explore the impacts of a selection of innovations that have either been piloted by authorities (e.g. use of 50% blend of recycled asphalt pavement and use of secondary resources such as construction rejects as an alternative to natural aggregates) (FM Conway, 2019; Hasan et al., 2020; Hossain et al., 2016; Purohit et al., 2021; Serres et al., 2016; Wijayasundara et al., 2017), commercially implemented alternatives (warm mix asphalt) (Rodríguez-Alloza et al., 2015; Vega-Araujo et al., 2020) and other conceptual measures integrating the use of bio-materials (use of bio-binders) (Do Nascimento Camargo et al., 2019; Espinosa et al., 2021; Fini et al., 2011; Samieadel et al., 2018; Sun et al., 2017).

Direct integration and comparison of the impacts reported for each of these innovations against the criteria for the conventional road pavement in this study is challenging. This is due to the anticipated differences in the systems analysed and compared, their geo-political boundaries and other 'cut-off' considerations. A threshold for carbon-savings was established for each of the sustainable alternatives, drawing from the findings about the relevant carbon savings that they deliver, acknowledging these uncertainties and differences. These quantifications were then analysed and normalised to the boundary constructs and analysis parameters of this study. Due to lack of primary data, these thresholds have been included as a means to explore possible reductions that could be acquired through the use of low carbon alternatives, in comparison with the baseline scenario, and therefore, must be treated with caution for real-world applications.

A baseline scenario, where the carbon sensitivity of conventional methods of construction (eg: bitumen binder, ordinary Portland cement, natural aggregates, and lime for sub-grade layers) is established and then compared to a range of resource efficient construction methods employing low carbon alternatives (Table 2). Due to lack of data, we assume that only virgin materials are used during the maintenance period in the baseline scenario and that any construction waste from the maintenance phase is disposed onto a landfill. This section will also explore the different resource efficient construction scenarios (RE_Scenarios) employing a mix of innovative and secondary materials.

Scenarios	Alternatives	Targeted materials	Targeted layer	Acceptable blend
Baseline	-	Hot mix asphalt construction	All the pavement layers	-
Scenario 1	Bio-binders	Asphalt binder	Binder course only	25%
Scenario 2	Crushed concrete and construction rejects	Natural aggregates	Sub-grade and sub-base	100%
Scenario 3	Crushed concrete and construction rejects	Natural aggregates	Sub-grade only	100%
Scenario 4	Warm mix asphalt	Hot asphalt mixture	Binder and surface course	-
Scenario 5	Recycled asphalt pavement	Fine aggregates	Surface course only	30%

Table 2: List of low-carbon and secondary alternatives to conventional road construction materials adopted for the sensitivity analysis

RE Scenario 1: Use of 25% blend of bio-binders as a greener alternative to neat asphalt binders; Application: Binder layer

Bio-binders are generally synthesised via different thermochemical routes (such as fast pyrolysis or liquefaction), depending on the source of the bio-oil. Only certain bio-oil sources (mainly vegetable oil, lignin and microalgal oil as opposed to used cooking oil and/or tallow) have been identified to be more suitable as bio-binder preparation since they exhibit improved fatigue performance and compression properties, comparable to asphalt bio-binders (Chailleux et al., 2012; do Nascimento Camargo et al., 2019b; Espinosa et al., 2021; Fini et al., 2011; Sun et al., 2017; Yang et al., 2014). Nevertheless, land-use emissions and the potential of these sources to introduce a “food vs. chemical” conflict must be carefully assessed. However, the extent of this performance varies with production methods, consistency, and combinations mixed with the asphalt binder. The bio-oil could be directly used as an asphalt modifier which enables the low-temperature performance and workability of asphalt during the pavement performance. Some studies have demonstrated that bio-binders can be applied as a total asphalt binder replacement, replacing 25% to 100% of the asphalt binder (do Nascimento Camargo et al., 2019b; Espinosa et al., 2021). Elaborate field and laboratory tests were observed to show no significant variations in their stiffness and permanent deformation, in addition to offering low moisture damage compared to neat asphalt binders. However, the authors who conducted this study acknowledge that long-term technical and environmental feasibility studies are required to be conclusive (Samieadel et al., 2018).

RE Scenario 2 and 3: Circularising construction rejects for use as secondary aggregates

Application (RE scenario 2): 100% secondary crushed concrete for the sub-grade/sub-base layer

Application (RE scenario 3): 100% crushed construction rubble as an alternative to natural aggregates for the sub-grade layer only

Use of downcycled aggregates was observed to reduce the overall GHG emissions by about 22-65%, compared to virgin aggregate use (Hossain et al., 2016; Serres et al., 2016; Wijayasundara et al., 2017). This, however, depends on the volume by weight of the lower layers. This reduction is observed from the coupled effects of displacing the need for natural aggregates and the affiliated demand for non-renewable energy. Downcycled aggregates mainly extracted from other commercial construction projects can either be crushed concrete or milled and reclaimed asphalt pavement. The quality of these downcycled aggregates (including low density and higher water absorption) has led to unstable compression strength and a generalised low expectation of their performance (Hou et al, 2014, Zhu et al, 2012, Chen and Wong, 2013). As a result, at the current state of technological maturity, they are recommended for use only in the sub-base and or base layers. Chemical treatment of these aggregates with bituminous emulsion, in combination with the use of slag-cement, has been recommended with additional treatment depending on the nature of the pavement (flexible/rigid) (Maduabuchukwu Nwakaire et al., 2020; Purohit et al., 2021).

RE Scenario 4: Use of warm mix asphalt as an alternative to the conventional hot mix method; Application: Surface and binder layer

Conventional hot mix asphalt is generally prepared at temperatures of about 140-160 °C to decrease the viscosity of the binding agents which is then mixed with aggregates. Besides binding, the purpose of this step is also to remove any excess moisture. Warm mix asphalt, on the other hand, is manufactured at a temperature that is on average 20-40 °C lower than hot mix (Rubio et al., 2012), though it does involve the use of a combination of modifiers such as zeolites, chemical/organic additives, emulsions, and water-based additives to reduce the viscosity of the aggregate-asphalt binder mixtures, thus improving its workability and mechanical properties. In addition, lower mixing temperatures, resulting in lower energy consumption, reduce the overall aerosol and carbon emissions delivering better environmental benefits both within the production facility and across the life of the asset. Moreover, shorter cooling times also correspond to shorter road closures (Hasan et al., 2020; Vega-Araujo et al., 2020; Vidal et al., 2013). However, these carbon savings are offset by the demand for the modifier technology leading to overall savings of only about 5-8%. Use of warm mix asphalt also supports the effective use of recycled/reclaimed asphalt pavement to be used as aggregates. On the other hand, the elimination of high temperature processing (which supports the effective moisture removal from the pavement mixture) leads to susceptibility to environmental moisture over time, in addition to hampering the binder-ageing process. This leads to premature rutting of the pavement thus requiring more frequent performance monitoring and doubling of maintenance routing (Rubio et al., 2012; Vidal et al., 2013).

Scenario 5: Blend of 50% Use of recycled asphalt pavement (RAP); Application: Surface layer only

Many studies (Arshad and Ahmed, 2017; Aurangzeb et al., 2014; Barham et al., 2021; Vandewalle et al., 2020) have characterised the performance of blended materials containing 50% reclaimed asphalt pavements used alongside fresh granular materials in the base and sub-base layers, focussing on the resilient modulus at baseline loading conditions. In addition to this, some stretches of motorway in England have been subjects of experimental evaluations of such innovations. RAP is synthesised by mixing reclaimed asphalt pavement with virgin aggregates leading to polymer-modified bitumen (PMB). However, further increases to the RAP content would affect the life of the pavement structure. Standards for highway design by National Highways dictates that the recycled content of the surface course may not exceed 10%. However, Transport for London (TfL) has piloted an increased blend of RAP substituting 50% virgin content on the surface course (45 mm) on a particular stretch of the A1 and A40. This has also been piloted by National Highways on a stretch of road M25, one of the busiest road networks in the country (FM Conway, 2019).

Road-interaction with a steadily decarbonising grid

National Grid, the UK's primary energy supply operator, achieved a reduction in direct GHG emissions by about 68% in 2020, compared to the 1990 baseline (National Grid, 2020). In 2020, renewable resources made up 42% of the UK's energy mix, outstripping the non-renewables contribution (Ambrose, 2021). The UK's largest electricity supplier is on track to achieve a 70% reduction by 2030 and 80% by 2050. This is likely to have a significant impact on the asset's whole life carbon, with the 'road operation' phase in continuous interaction with the energy grid.

National Grid, in collaboration with key industrial stakeholders, published 'Future Energy Scenarios 2020', which explores a range of pathways that employ a combination of innovative energy supply technologies that could potentially assist the sector to achieve net-zero by 2050. The aim of this model is to help the 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 the FES 2020 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 initiatives lie with the integration of innovation at the supply side; Fossil fuels are effectively replaced by electrification 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 road 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 adaption 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 on 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 includes 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 behavioural 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 for the electricity mix for the various scenarios for the analysis years 2020 and 2050 (based on FES2020 estimates) have been presented in the Table 3. The corresponding carbon-intensity for the electricity mix generated from the different pathways is assumed for the embodied 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 road ‘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 3: Electricity mix (in % contribution) over the different pathways (over 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 supply-side’s evolution towards the production and distribution of low-carbon energy. The two adopted pathways will be referred to as ‘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 ‘road-operation’ sub-system that is 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 functional unit of this analysis. It is acknowledged the grid decarbonisation pathways have been applied only for the road-operation (lighting only) 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[3] and/or DACCS[4]) 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. Hereon, 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 assumes a ‘CCS’ setting where transport infrastructure acquires access to negative carbon produced by the aforementioned technology.

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[3] BECCS: Bioenergy with Carbon Capture and Storage

[4] DACCS: Direct Air Carbon Capture and Storage

3 Impact assessment – results interpretation

The whole life carbon impacts presented in this section account for the embodied carbon in the materials sourced for the construction process during the first year (year of installation) and the energy and material supply required for the operation (of road lighting) and maintenance of 1 km of road over a period of 40-years. A breakdown of the carbon contributions from these different stages has been presented in Table 4.

Asphalt pavement sub-systems	**Dual-3 lane**	**Dual-2 lane**	**Single-2 lane**
	tCO_2eq per functional unit		
Material production	1,711	1,433	591.5
Material transport	313	201.3	100.7
Construction	70	37.6	18.8
Road operation (lighting only) (40 yrs.)	406.1	2,68.7	132.6
Maintenance (40 yrs.)	158.8	73.5	36.6
Total emissions	2,658.9	2,014.1	880.3

Table 4: Embedded emissions estimated for the different sub-systems of asphalt pavement (for different scales of construction) over an assumed time period of 40 years (also the 'baseline' scenario).

The embodied carbon estimated for 1 km of single carriageway (asphalt, via hot method construction), is comparable to that estimated within the Inventory of Carbon and Energy[5]. The percentage variation between the two estimates was observed to be less than 5%, validating the whole life estimates for the asphalt pavement that are to be adopted into the sensitivity study.

In general, the materials required for the asphalt pavement had a significant proportion of embodied carbon contributing 67-75% of the whole life GHG emissions across the different construction scales (**Error! Reference source not found.**). Studying the elemental contribution, c oncrete and asphalt binder production were jointly responsible for 75% of the production emissions (131 $kgCO_2eq$ and 40 $kgCO_2eq$ per tonne of material produced) (Department for Environment, 2020). This was followed by the emissions attributed to the power supply for road lighting operation (16-18%). The carbon contributions reported so far are likely to be influenced by the variation in the 'material transport' emissions (distance between the source location of the materials and the location of the construction site).

Production of asphalt mix for paving the surface course and cement for the lower layers makes the surface course the most energy-intense layer (4.98 TJ), including energy incurred by the maintenance phases over the asset's 40-year lifetime. Roughly 60% of the embodied carbon is estimated to be in the surface and the binder course of the pavement. The relatively high carbon intensity and the embodied energy of the construction materials stems from the energy intensity of the processes associated with their production and the energy spent transporting them between facilities and to the construction site. A breakdown of the energy flow through each of the layers in asphalt pavement has been presented in Figure 5.

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[5] Commonly known as ICE, standard carbon factor database used in the National Highways Carbon Tool and the RSSB Rail Carbon Tool.

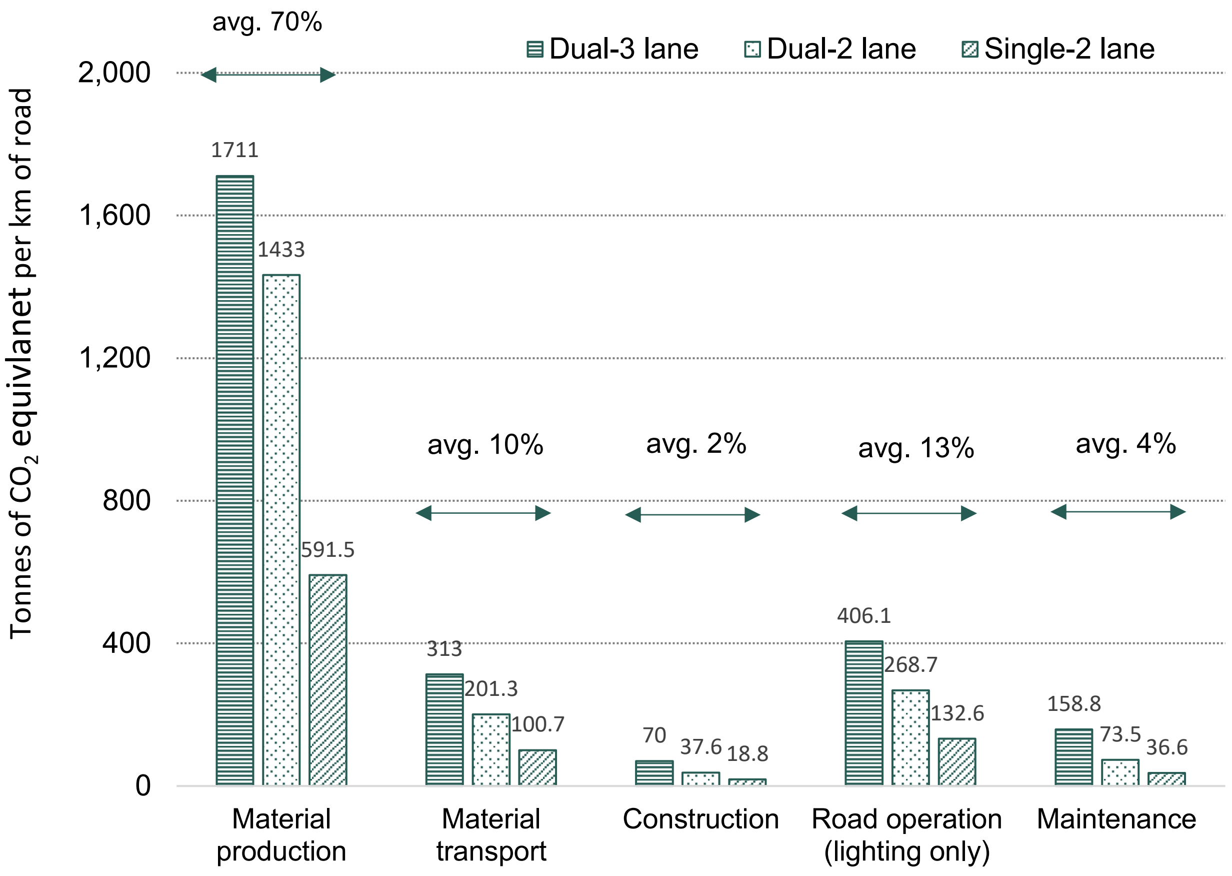

Figure 4: Life cycle carbon emissions associated with different scales of asphalt pavement construction

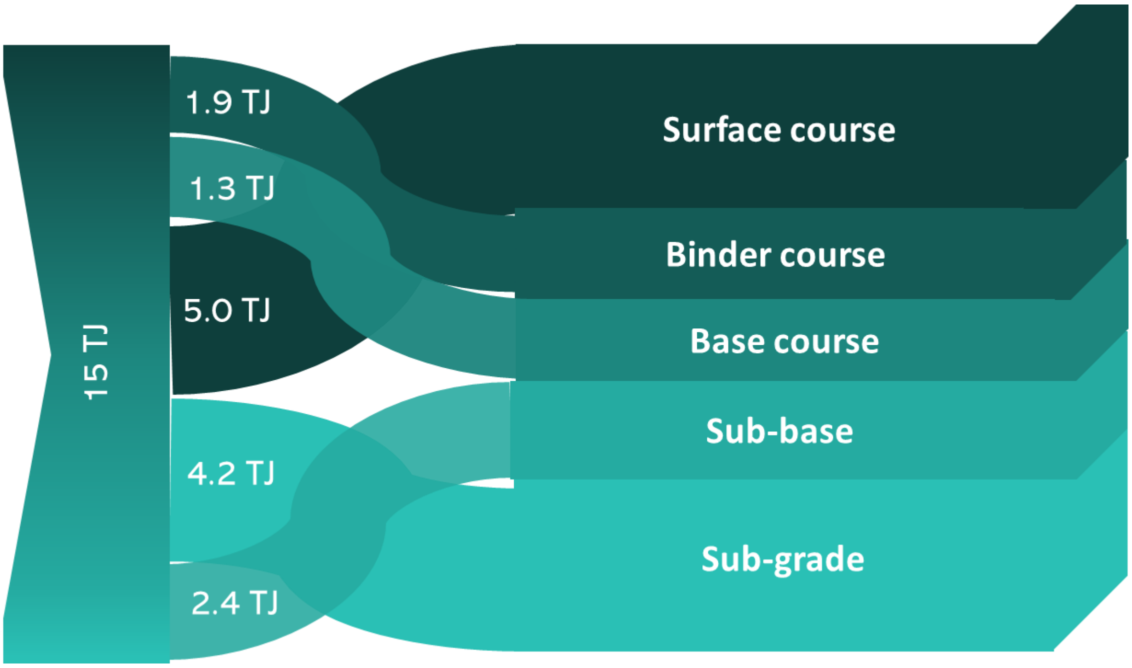

Figure 5: Embodied energy within each layer of the asphalt pavement

3.1 Sensitivity analysis

Integration of sustainable alternatives

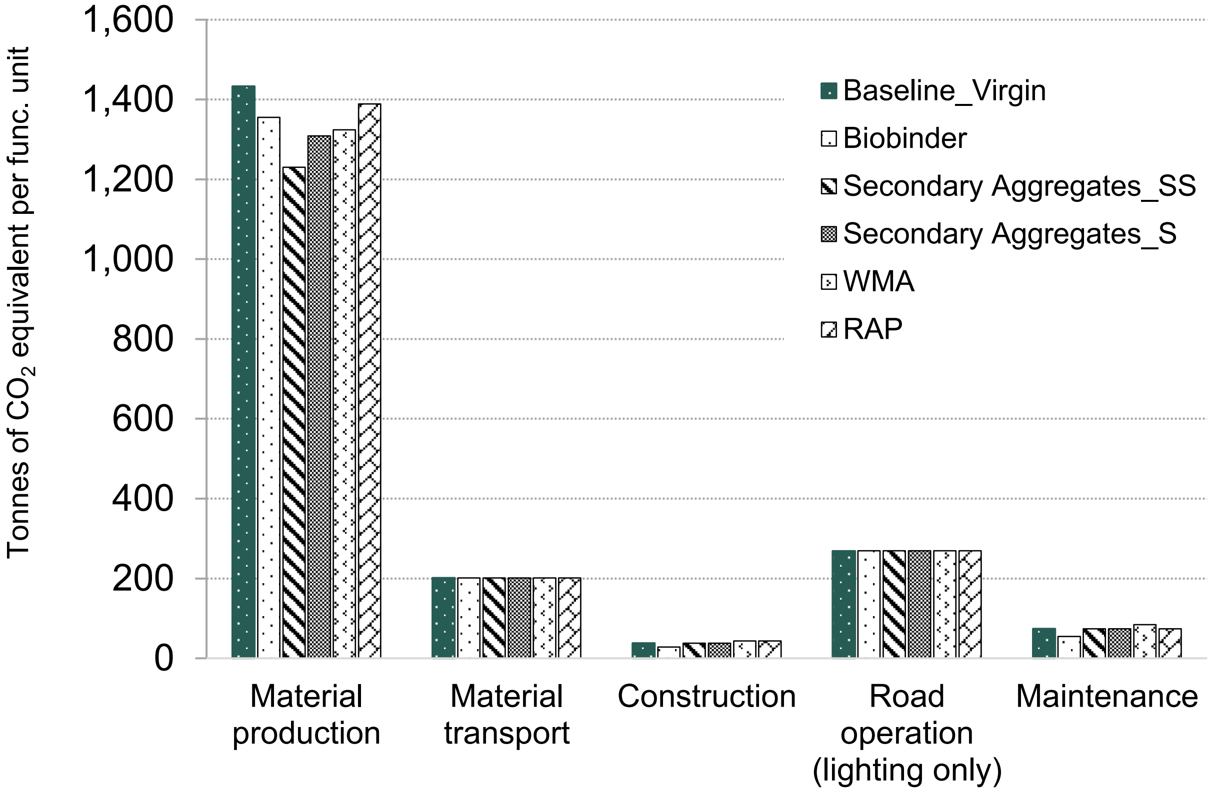

Figure 6: Sensitivity of the embodied carbon of a functional unit of study (baseline highlighted in 'green') to the integration of low-carbon alternative materials and technology

The above reported embodied carbon figures are affected by the quantity and the type of secondary resource integrated into the asphalt pavement practices. The best plausible resource efficiency scenario, which entails the use of 100% crushed concrete and construction rejects, as an alternative to natural aggregates, (RE_scenario 2) was observed to show the lowest overall carbon emissions, compared to the other sustainable alternative strategies. Accounting for nearly 50-60% by mass of all the input materials, replacement of all the aggregates in specific layers of the construction were investigated. 100% replacement of natural aggregates with crushed concrete and construction rejects in the sub-grade and sub-base layer (RE_scenario 2) led to an overall GHG emissions reduction by about 10%, displacing virgin materials production and subsequent emissions by 12%. The mechanical performance of these secondary resources, in terms of response to long-term load stress, abrasion and subsequent alteration of the road track bed's drainage characteristics have been questioned by a number of studies, though rarely conclusive (Hossain et al., 2016; Maduabuchukwu Nwakaire et al., 2020; Mineral Products Association, 2020). Scenario 3 caters to this uncertainty, restricting the 100% replacement of natural aggregates just to the sub-grade layer. This led to carbon savings in the range of 4-12%, compared to the baseline case-study, while still being lower than that reported for RE_scenario 2 (Figure 6).

Dual-3 lane	**RE_ Scenario_1**	**RE_ Scenario_2**	**RE_ Scenario_3**	**RE_ Scenario_4**	**RE_ Scenario_5**
	Tonnes of CO_2 equivalent per F.U.				
Material production	1,590	1,403	1,644	1,517	1,542
Material transport	313	313	313	313	313
Construction	53	70	70	80	80
Road operation (lighting only)	406	406	406	406	406
Maintenance	74	159	74	84	74
Net emission	**2,435**	**2,351**	**2,506**	**2,400**	**2,414**
% carbon savings (relative to baseline)	8.39	11.55	5.72	9.71	9.18
Dual-2 lane	Tonnes of CO_2 equivalent per F.U.				
Material production	1,355	1,230	1,309	1,324	1,389
Material transport	201	201	201	201	201
Construction	28	38	38	43	43
Road operation (lighting only)	269	269	269	269	269
Maintenance	55	74	74	84	74
Net emission	**1,908**	**1,811**	**1,890**	**1,920**	**1,975**
% carbon savings (relative to baseline)	5.26	10.08	6.16	4.67	1.94
Single-2 lane	Tonnes of CO_2 equivalent per F.U.				
Material production	544	495	548	515	556
Material transport	101	101	101	101	101
Construction	14	19	19	16	16
Road operation (lighting only)	133	133	133	133	133
Maintenance	37	37	37	42	37
Net emissions	**828**	**784**	**837**	**806**	**842**
% carbon savings (relative to baseline)	5.94	10.94	4.92	8.44	4.35

Table 5: A comparison of embodied carbon estimates for the different resource efficient scenarios over an assumed 40 year life period.

As for other RE_scenarios, using bio-binders as an alternative to asphalt binders is restricted to a maximum of 25% blend (RE_scenario 1) to avoid compromising the stress-bearing and rutting performance of this crucial binder course. Comparatively, the material carbon for the binder layer reduced by 20%, with minor reductions observed in the maintenance phase. These reductions are mainly attributed to the significant energy savings from the removal of ‘energy-intensive’ asphalt binder mixing, and subsequently, from further savings from the ‘construction’ sub-system. Use of RAPs is a well-known approach within pavement decarbonisation strategies. However, the limited availability of acceptable quality RAPs and the demand for high-impact chemical modifiers/rejuvenators outweigh, and sometimes neutralise, any carbon benefits. Blending milled recycled asphalt pavement with the virgin mix is observed to deliver an overall GHG emissions savings in the range of 10-16% on surface course carbon. However, these savings dropped to 2-9% due to the need for more frequent road resurfacing to keep the pavement functional and to acceptable standards. Some studies have identified that the wearing of the aggregate content in the RAP (that may have had over 20 years of service life) lead to the reduced durability and stress resistance with its reuse, compared to the baseline case (Gillespie, 2012; Hasan et al., 2020; Purohit et al., 2021). Use of warm mix asphalt (RE_scenario 4) reduced the GHG emissions relevant to the surface course by about 4-10% resulting from a lower energy demand to heat the asphalt mix. The elimination of this high-temperature phase leads to a gradual degradation of the surface course from prolonged exposure to moisture damage. This leads to trade-offs in carbon savings from an increased maintenance routine which reduces the carbon efficiency. Quantified embodied carbon estimates for each of the 5 scenarios have been presented in Table 5.

Integration of a steadily decarbonising grid

Impact of grid decarbonisation on road-lighting operations only

The operation and maintenance of a road’s electrical systems is comparatively energy efficient compared to a decade ago (Hanson et al., 2012; Milachowski et al., 2018; Stripple, 2001; Trunzo et al., 2019). A more optimised lighting operation from 2020 onwards, employing the ‘Steady Progression’ and ‘System Transformation’ pathways, is determined to be a further 58% to 84% more carbon-saving.

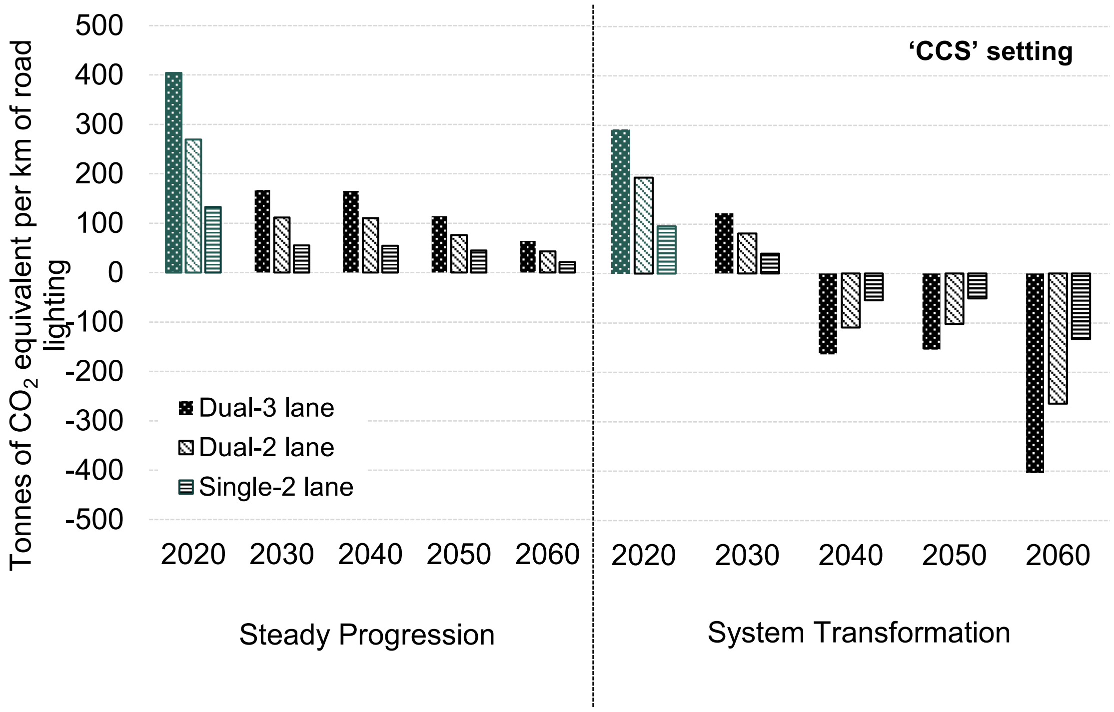

Figure 7: Net carbon emissions per kilometre of road from the integration of the two grid decarbonisation pathways, under the ‘CCS’ setting, to road light operation only (Note: Baseline scenario highlighted in ‘green’; for the System Transformation pathway, strong reliance on CCS: hypothetical scenario)

The significantly lowered carbon intensity comes from the deployed low-carbon energy systems, supported by a robust energy policy landscape that has been assumed within the ‘Future Energy Scenarios’ modelling and, thus, within this sensitivity study. For example, among the four scenarios, the ‘Steady Progression’ pathway adopts the slowest pace for transformation in the technological innovations and consumer behavioural shift. As a result, there is a steady and significant reliance on fossil fuels (natural gas) for electricity supply, right up to the net-zero year, 2050. Subsequently, within the ‘Steady Progression’ pathway, the national energy grid is decarbonised by only about 58-84% when powering road-lighting operation for between 2030 and 2060, relative to that of the present energy supply.

Under the ‘System Transformation’ pathway, there is a significant shift to low-carbon energy systems where roughly 82% of the electricity is expected to be generated from renewables; particularly, on/offshore wind and bioenergy, with BECCS contributing some level of carbon abatement, from 2030 to 2050. Use of fossil-fuels for electricity generation is assumed to be eliminated by 2040, thus assisting the energy sector to reach net-zero by 2050. Without likely access to negative carbon, the reduction in carbon intensity of road-lighting operation was observed in the range of 70-200% between the 2030 and 2060, relative to the 2020 estimates. The FES energy modelling shows that BECCS facilities do not contribute to the electricity mix until 2028. Particularly, the carbon intensity of BECCS-based electricity supply depends on its sequestration potential, nature of the bioresource mix, logistics and carbon storage stability. The successful deployment of these technologies is uncertain both in economic feasibility and timescale. It seems unlikely that there will be BECCS at sufficient scale to apply to this case. However, this is a scenarios exercise, and the ‘Steady Progression’ pathway provides a scenario where assumptions on the integration of hydrogen and BECCS is limited, as opposed to ‘System Transformation’. Carbon emissions attributed to operating the road lights over the temporal boundary of 40 years has been presented in Figure 7 for both the pathways.

Impact of grid decarbonisation on whole life carbon

Factoring the observed variations in carbon intensities for road-lighting into the whole life carbon estimates under the ‘no CCS’ setting and ‘Steady Progression’ pathway, the threshold for carbon savings (between 2030-2060) is between 8-17.6%, relative to the 2020 estimates, while under the ‘System Transformation’ pathway, the carbon savings are about 9-42% of the 2020 estimates, for the different scales of construction (Dual-3, Dual-2 and Single-2). A comparison of the whole life carbon estimated for a functional unit of study for baseline and resource-efficient scenarios, under the two adopted grid-decarbonisation pathways has been presented in Figure 8 and Figure 9.

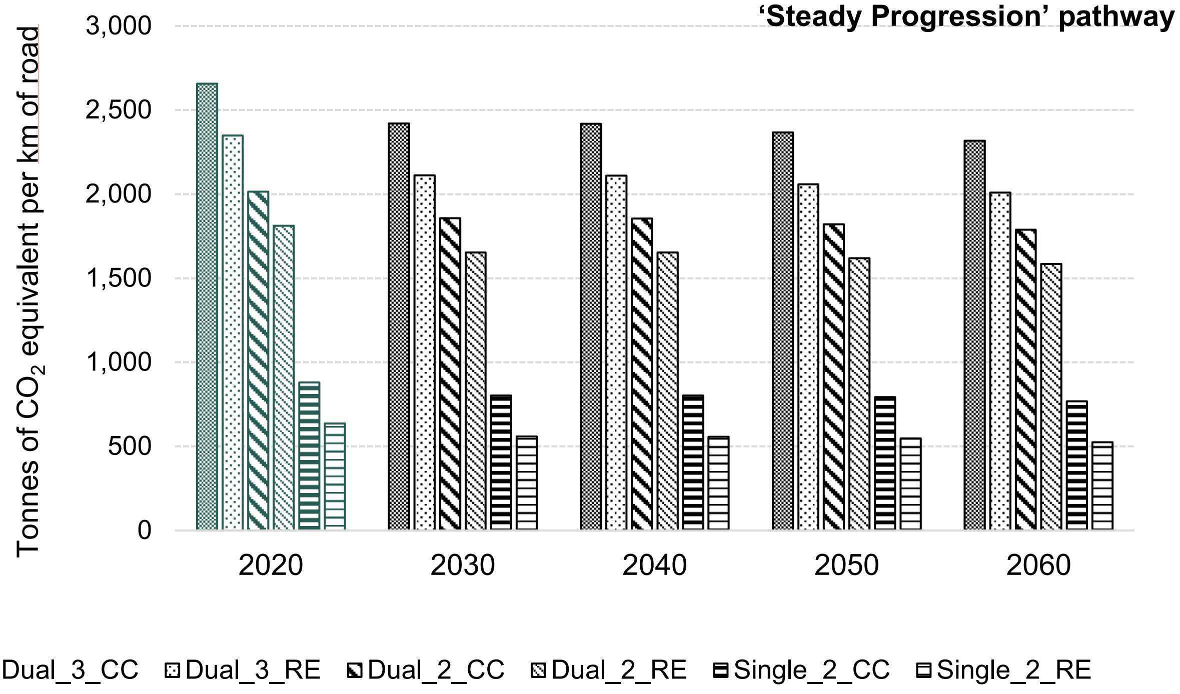

Figure 8: Impact of the energy sector decarbonising via the 'Steady Progression' pathway on the whole life carbon of 1 km of road constructed via conventional and the most carbon efficient methods (RE_Scenario 2), over the service life of 40 years (presented for Dual-3, Dual-2 and Single 2 lane) (Note: Baseline scenario highlighted in 'green')

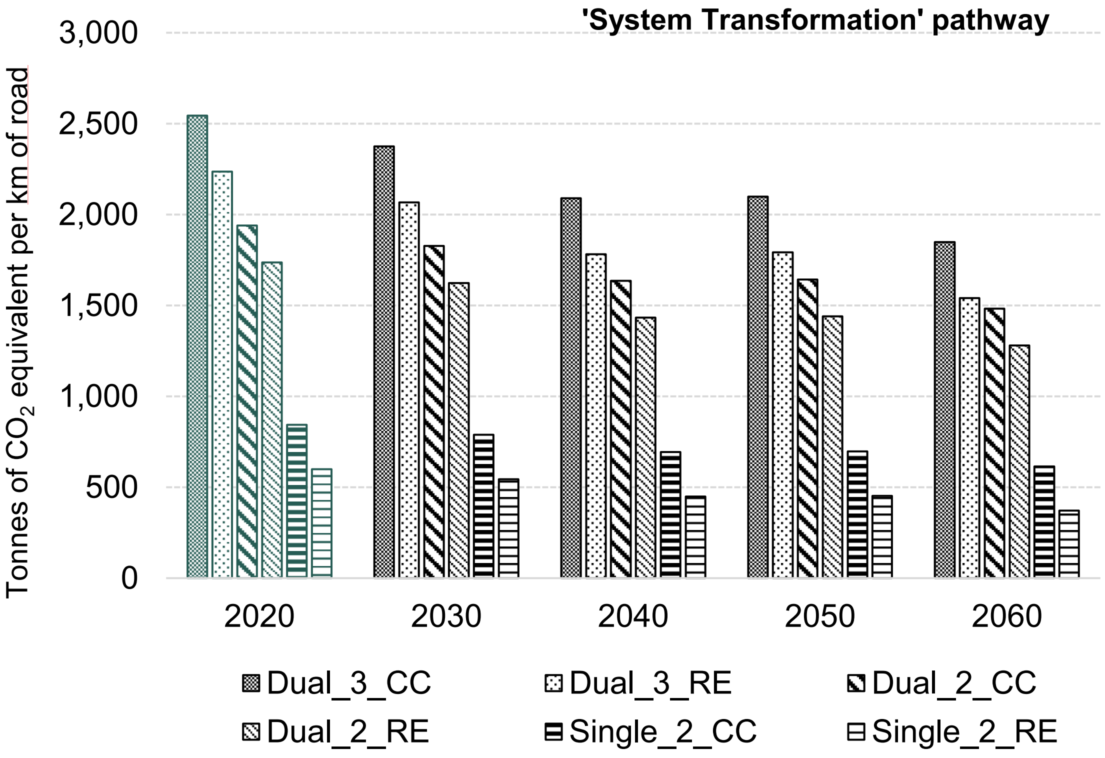

Figure 9: Impact of the energy sector decarbonising via the 'System Transformation' pathway on the whole life carbon of 1 km of road constructed via conventional and the most carbon efficient methods (RE_Scenario 2), over the service life of 40 years (presented for Dual-3, Dual-2 and Single 2 lane) (Note: Baseline scenario highlighted in 'green')

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

4.1 Case 1: Scheme 42: A19 junction and on-line improvements between Killingworth interchange and Coast Road/Silver link interchange

Figure 10: Scheme length, location and the 'street view' of the A19 junction and on-line improvements between Killingworth interchange and coast road/Silverlink interchange, planned for the route upgrade

Temporal boundary	40 years
Spatial coverage	The A19 mainline, North Tyneside, North East England
Link length	8.1 km

Scheme description: The A19, a major road in the North of England, runs parallel to the A1 connecting the Doncaster (South Yorkshire) with Seaton Burn (Tyne and Wear) (Figure 10). The scheme section is 8 km long between Killingworth and Coast Road/Silverlink Interchange providing access to the Tyne Tunnel further from the south end of the scheme. Some of the key areas along this route include the Tyne Tunnel trading estate and the Silverlink Shopping Park at the south end to Annitsford at the north end of the scheme, covering Killingworth and Northumberland Interchange along the route.

Planned developments: The current two-lane dual carriageway (assumed 7.2 m wide) is planned for widening into a three-lane road (assumed an additional 3.6 m to the 7.2 m each way), to improve road capacity, addressing the issues of congestion and frequency of accidents. The lane widening is assumed to include the bridge crossing the A191 and A186 gyratory. This major route is an asphalt construction. The illuminated stretch (road surface with lighting) on this link is 0.8 km long. Road lighting on this stretch is also assumed to be repositioned and reinstalled. The exit lanes are upgraded to accommodate the grade separations from the extended lanes to the west and east of the A19 mainline. The existing traffic lights at the junctions of the gyratory are also expected to be replaced.

To estimate the embodied emissions in the planned development, the resource expenditures had to be first quantified. The additional land area that is required to be cleared of vegetation in preparation for lane-widening, the construction including foundation reinforcement, designing the drainage characteristics, pre-cast concrete barriers to separate routes for construction vehicles and the road users, water supply, and site office operation impacts were all factored into this analysis.

The whole life carbon is estimated for the construction, operation, and maintenance of the scheme, over an assumed life period of 40 years. Like the sensitivity evaluation of the benchmark in the earlier sections, the schemes were also subjected to resource efficiency practices applying the most carbon efficient approach (RE_scenario 2), in addition to the two grid-decarbonisation scenarios (‘Steady Progression’ and ‘System Transformation’).

Impact assessment: Scheme 42: A19 junction and on-line improvements between Killingworth Interchange and Coast Road/Silverlink Interchange

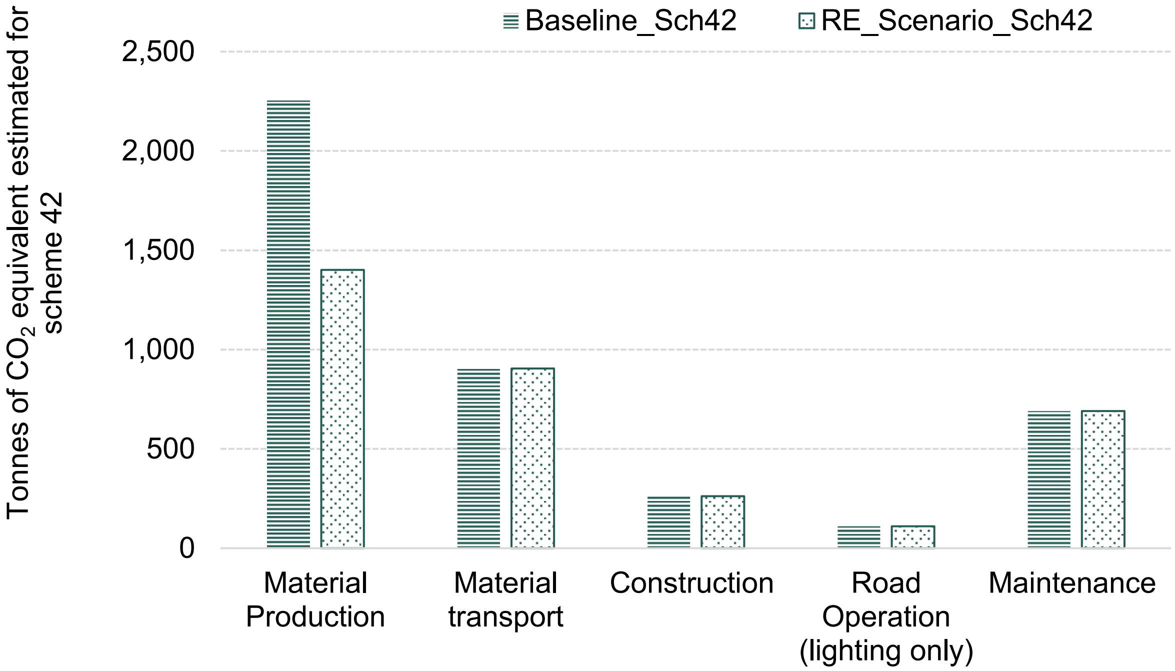

Figure 11: Embodied and Operational carbon estimated for scheme 42: A19 junction and on-line improvements between Killingworth Interchange and Coast Road/Silverlink Interchange

The whole life carbon of all the planned development in this scheme through conventional and resource efficiency construction is about 4,816.6 tCO_2eq and 3,370.8 tCO_2eq. 70% of the whole life emissions are embedded in the materials sourced and transported for pavement construction, while a further 14% is attributed to the maintenance of this scheme (Figure 11). The primary emission contributors within the material production was the asphalt binder production (23%), followed by the concrete and steel (20%) required for the bridge expansion to accommodate the widened lane over the A191/A186 gyratory. This shows that the scheme comprises significant levels of 'hard-to-decarbonise' phases in its overall life cycle.

From a resource efficiency perspective, the resource-efficient build is 30% more carbon efficient compared to the conventional approach. These carbon savings are due to the combined effects of using site-won soil and crushed concrete to reinforce the foundation layers of the pavement. This includes the use of about 15% blend of reclaimed asphalt as aggregates for the sub-base layer to displace carbon emissions from virgin material consumption while the mechanical integrity and performance of the sub-base layer is assumed to remain unaffected.

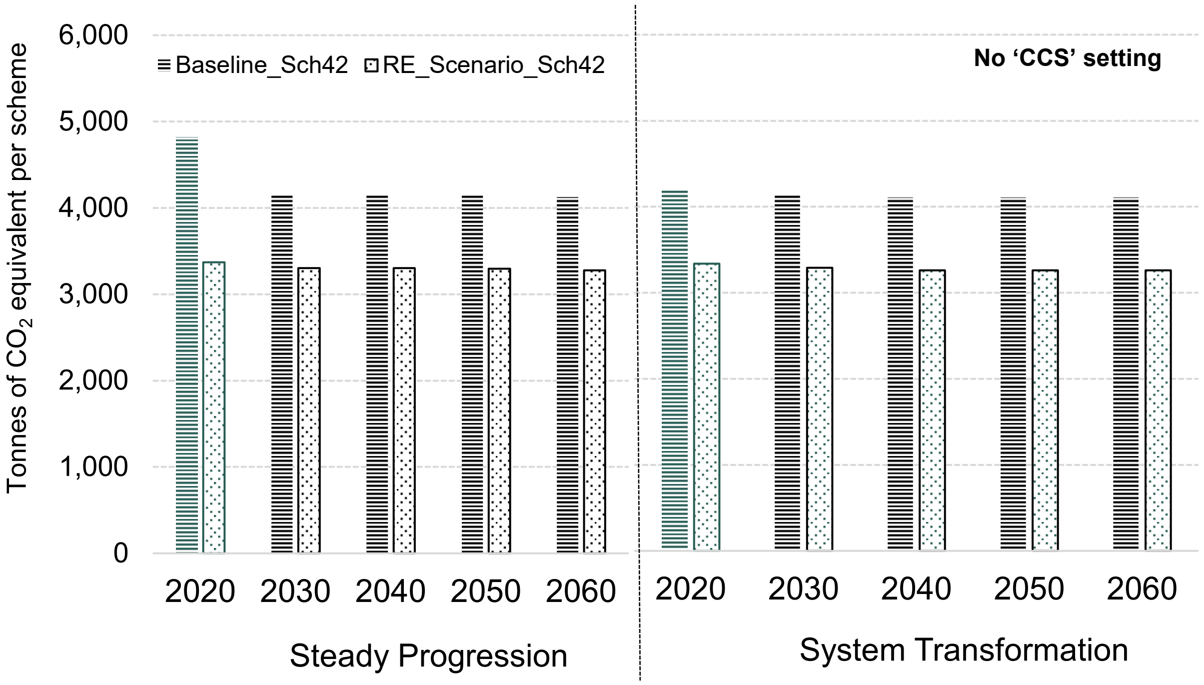

Figure 12: Whole life emissions estimated for scheme 42, applying the impacts of a steadily decarbonising grid, if constructed and operated between 2020 and 2060, under a 'no CCS' setting, (Baseline_Sch42: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch42: Resource Efficient build using circular and secondary materials suitable for pavement construction)

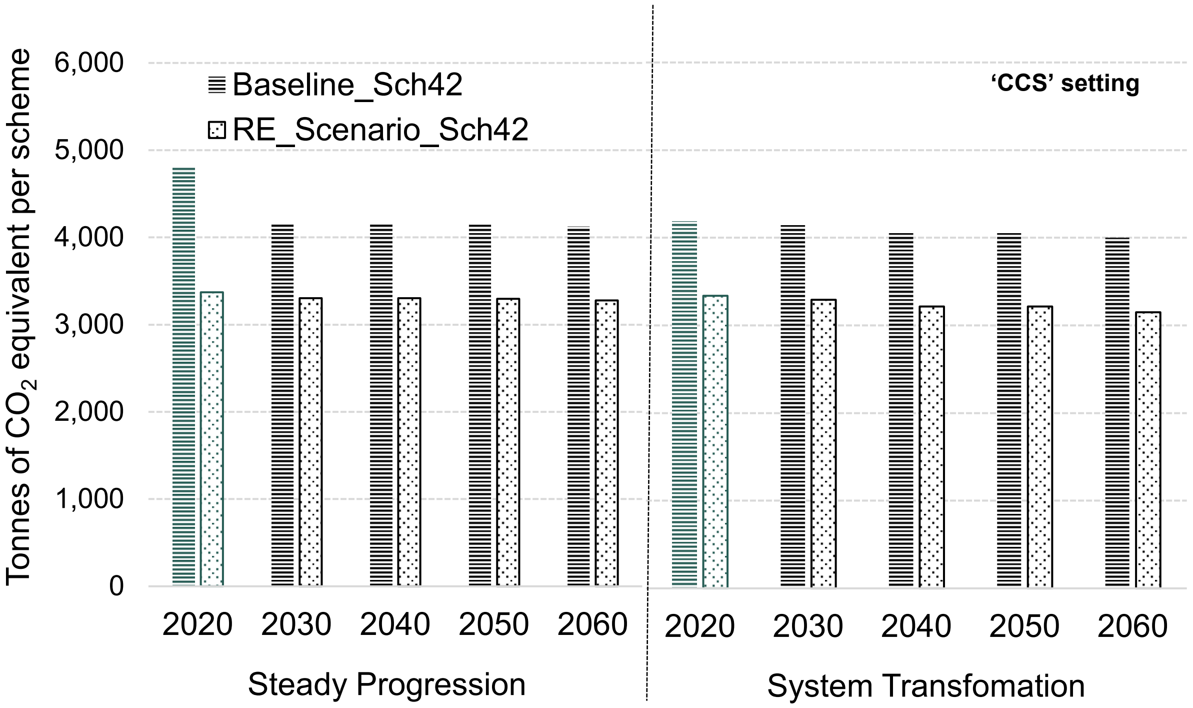

Figure 13: Whole life emissions estimated for scheme 42, applying the impacts of a steadily decarbonising grid, if constructed and operated between 2020 and 2060, under a 'CCS' setting; (Baseline_Sch42: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch42: Resource Efficient build using circular and secondary materials suitable for pavement construction)

The energy sector is steadily decarbonising through strategic adoption of low-carbon technologies, investments and an overall improvement in energy efficiency practiced at both the ends of demand and supply. Within the road-infrastructure, there is a continuous interaction between the built assets and the energy grid, for lighting purposes. Specifically, in road infrastructure, the operational carbon is directly influenced by road lighting, traffic lights, CCTV and speed enforcement cameras. This scheme only has a set illuminated stretch of 0.8 km equipped with road lighting, which was assumed to be maintained, so requiring additional lighting for the extended road surface. There are roughly 15 traffic lights at the A191/A186 gyratory which are assumed to be repositioned and installed equipped with energy efficient LED lighting. The difference in operational energy use upon widening the two-lane carriageway to a three-lane carriageway was determined to be 2.2 TJ for road lighting and 0.9 TJ for the traffic light operation.

The carbon intensities of the electricity mix from the two grid decarbonisation scenarios were integrated for every 10 years between 2030 and 2060 to road light operation only. The conventional build was 13-17% more carbon-saving, when compared to its 2020 baseline following the Steady Progression scenario (baseline highlighted in green) (Figure 12 and Figure 13). The resource-efficient build was 32-34% more carbon-efficient, when compared with the 2020 'Steady Progression' pathway (baseline highlighted in green in Figure 12 and Figure 13). These savings amount to roughly 1,500-1,660 tCO_2eq. It is to be noted that this carbon efficiency reported for the resource-efficient scenario, represents the combined effect of both material-based savings and the decarbonising grid electricity. Despite the significant decarbonisation of the energy sector over our analysis period (-82% in 2060, compared to 2020), the carbon savings are barely observed in our scheme's carbon estimation. This can be attributed to road-lighting making up only 5% (0.8 km out of 8.1 km illuminated) of the whole life carbon emissions of the scheme. In a 'no CCS[6]' setting, we observe carbon savings drops to 13-14% and 30-32% for the conventional and resource-efficient construction scenarios.

4.2 Case 2: Scheme 44: A19/A1056 Killingworth, Upgrade of junctions at slip roads to the west and east of the A19 mainline

Figure 14: Scheme length, location and, satellite image of the A19/A1056 Killingworth, planned for the junction upgrade

Temporal boundary	40 years
Spatial coverage	The A19 mainline, North Tyneside, North East England
Scheme Length	1.1 km

Scheme description: This scheme is based on the A19 mainline described in Scheme 42. These slip roads from the A19 mainline lead to Killingworth to the west and Backworth/Holywell to the east (Figure 14).

Planned Developments: Planned upgrades to the slip roads are expected to entail widening of exit lanes, repositioning, and installing energy efficient road lights, and on-line realignment of the eastbound and westbound single carriageways.

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[6] 'No CCS' setting could only be applied to the sensitivity study that had embedded the 'System Transformation' scenario, as it is the only acceptable net-zero grid decarbonisation scenario that we have adopted in this study. Please see 0 for more details.

Impact assessment: Scheme 44: A19/A1056 Killingworth, Upgrade of junctions at slip roads to the west and east of the A19 mainline

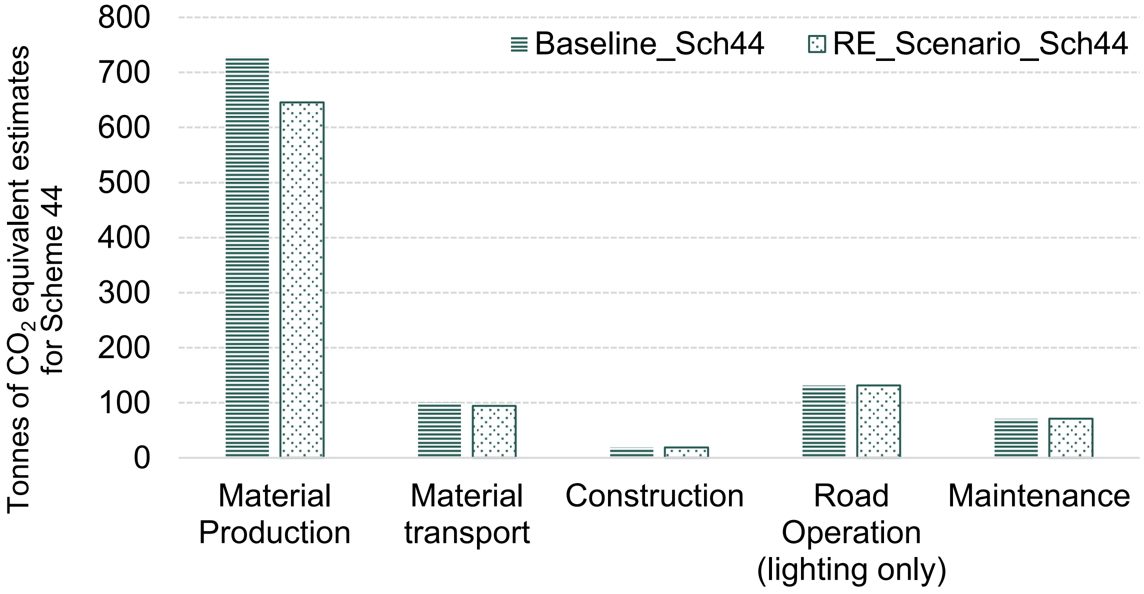

Figure 15: Embodied and Operational carbon estimated for scheme 44 at the A19/A1056 Killingworth

The whole life carbon profile for the developments assumed in scheme 44 has been presented in Figure 15. As observed in the earlier case study, the embodied carbon in the construction materials contribute an average of 70% of the whole life carbon. This is followed by the emissions from energy demand for road light operation (13% of the overall emissions), closely followed by emissions from material transport. Material transport emissions could be affected by the source location of the construction materials, which in turn will affect the inference on which is the second most carbon contributing life cycle stage.

Widening the slip roads to cater for the grade separation from the extended lanes in the A19 mainline is evaluated in this section. Compared to the conventional use of materials for the pavement construction (CC), the resource efficient build delivered whole life carbon savings of about 8.5%. The carbon savings are relatively lower, compared to that observed in scheme 42, partly due to the scale of construction demanding fewer restraint systems and relatively lower quantities of secondary material use. Use of secondary and reclaimed materials (crushed concrete in the place of natural aggregates, fly ash for foundation stabilisation) for this scheme, however, displaced 13% of virgin material emissions. Yet, in both the scenarios, material production accounts for 67-70% of the embedded carbon, over the year of scheme completion. In this case study, road lighting account for about 12% of the overall emissions (Figure 15).

When applying the ‘no CCS’ setting for grid decarbonisation to this scheme’s road-light operation emissions, the maximum carbon savings are restricted to 8-12% for the conventional build (carbon savings of 92 to 261 tCO_2eq) and between 17-21% for the resource efficient construction (carbon savings of 161 to 274 tCO_2eq), relative to 2020 figures under the ‘steady-progression’ pathway (Figure 16). When applying the ‘CCS’ setting, for the same time period, the range for carbon efficiency could be extended slightly 8-13.5% (carbon savings of 92 to 293 tCO_2eq) and 17-24% (carbon savings of 161 to 350 tCO_2eq), compared with the baseline estimation presented above (Figure 17). This holds only for conventional choice of construction. Construction employing resource-efficient approaches was 15-19% and 17-33% more carbon efficient, under the scenarios of the same order. The disparity in the whole life carbon observed between the ‘conventional’ and the ‘no CCS’ scenario is the result of the scale of construction and hence the material demand for the scheme. As presented earlier, the material demand for the construction and maintenance dominates the whole life carbon of the scheme.

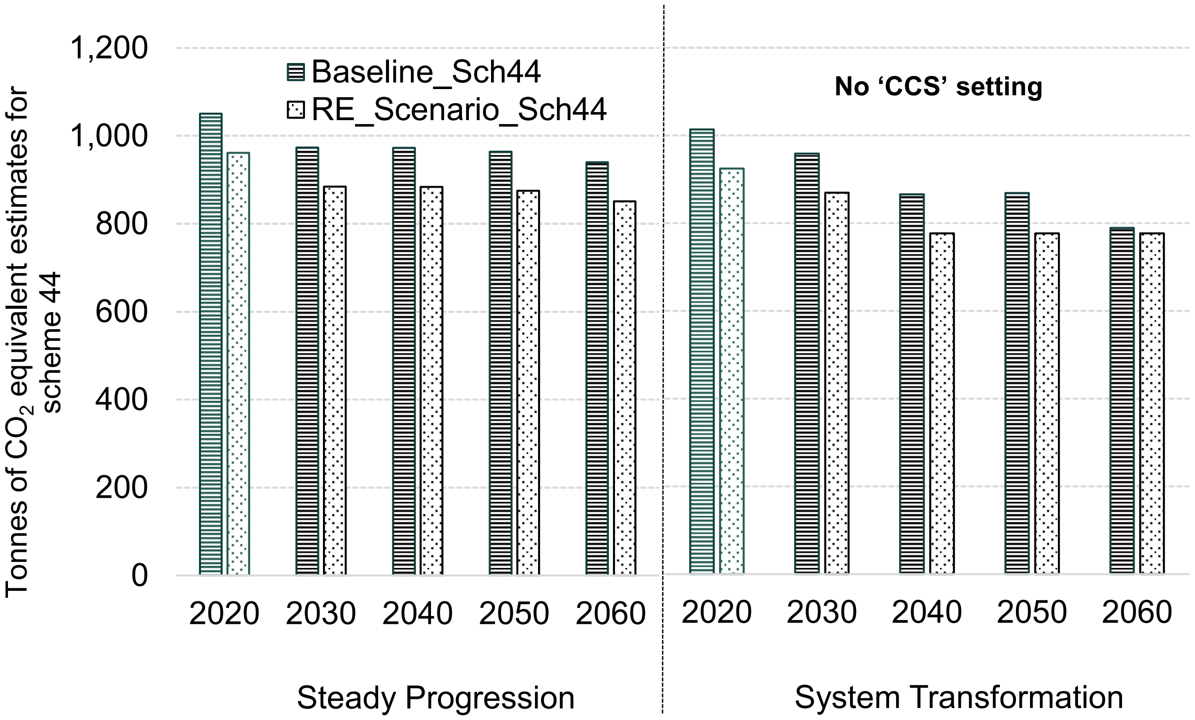

Figure 16: Whole life emissions estimated for scheme 44, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a ‘no CCS’ setting, (Baseline_Sch44: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch44: Resource Efficient build using circular and secondary materials suitable for pavement construction)

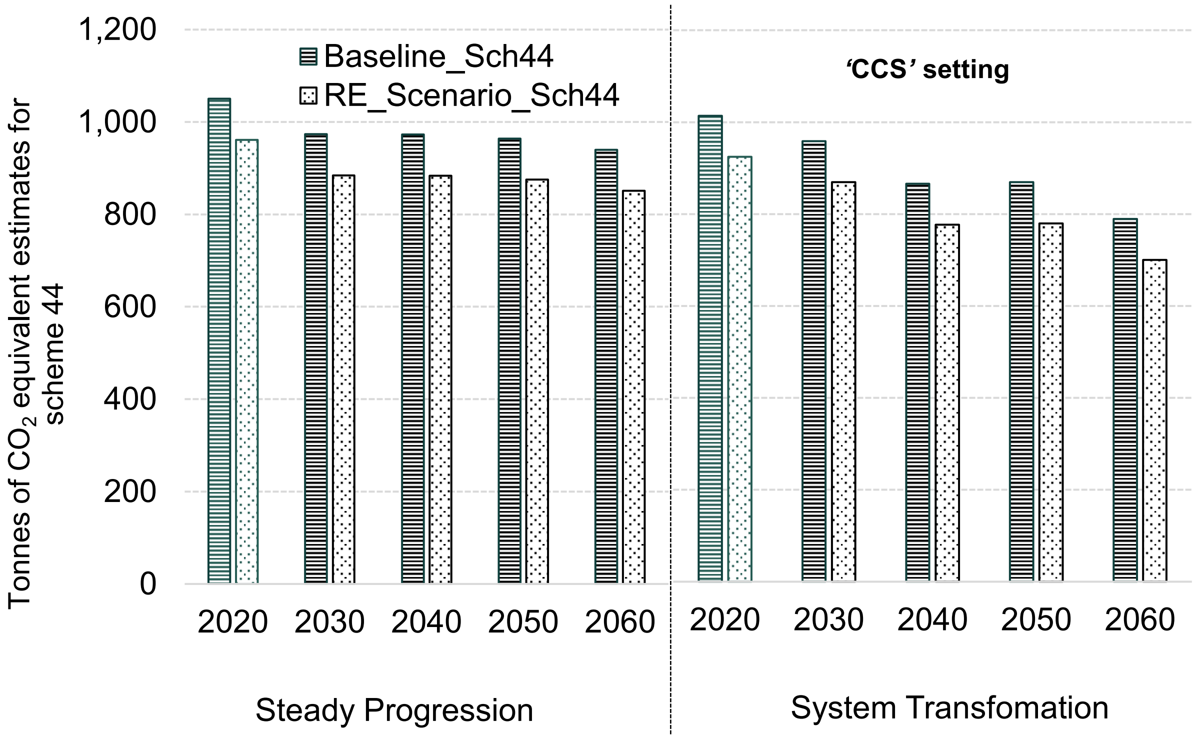

Figure 17: Whole life emissions estimated for scheme 44, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'CCS' setting, (Baseline_Sch44: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch44: Resource Efficient build using circular and secondary materials suitable for pavement construction)

4.3 Case 3: Scheme 139: A1068 Fisher Lane, dualling of A1068 Fisher Lane to the west of Cramlington. Dualling assumed between Seaton Burn and Cramlington

Figure 18: Scheme length, location and the 'street view' of the A1068 Fisher Lane, between Seaton Burn and Cramlington, planned for the route upgrade

Temporal boundary	40 years
Spatial coverage	The A1068 – Northumberland, North East England
Link length	2 km

Scheme description: The A1068 is a road in the North of England which branches off the A19 before the latter joins the A1. Running between Seaton Burn in North Tyneside and Alnwick in Northumberland, A1068 has a brief stretch of dual carriageway, just after branching off the A19 (roughly 1 km long) (Figure 18). The rest of the Fisher Lane is an asphalt based single carriageway. The illuminated stretch of this link is about 0.7 km long.

Planned developments: The single carriageway on Fisher Lane is assumed to be supported with lane extension each way transforming into a dual-2 lane carriageway between Seaton Burn and Cramlington. It is also assumed to be equipped with a plain-kerbed central reservation following on from the dualled stretch branching off of the A19. The road lights in the illuminated stretch are expected to be repositioned and fitted with energy-saving LED lighting. This extension will be seen through to the exit lanes leading to the A1068/A1172 gyratory.

Material and energy inventories for this construction were gathered and the carbon impacts of the scheme's construction, maintenance and operation were modelled and quantified.

Impact assessment: Scheme 139: A1068 Fisher Lane, dualling of A1068 Fisher Lane to the west of Cramlington. Dualling assumed between Seaton Burn and Cramlington

The whole life carbon profile of the scheme, incorporating the emissions attributed to the planned development activities, is presented in Figure 19. The whole life carbon profile for the proposed scheme showed that material production accounted for 70-74% of the whole life carbon estimated for this scheme, followed by that for material transport (12-13%). Construction employing secondary and reclaimed resources for the sub-grade and the sub-base layers delivered carbon savings of about 12.7%. This involved use of crushed aggregate and reclaimed asphalt alongside natural aggregates. This also includes the use of fly ash from municipal solid waste (MSW) incineration plants, for the reinforcement of the pavement foundation. The key carbon hotspots of this scheme are mainly the material and energy consumption related to the production and preparation of asphalt binder mix for the binder and the surface layer of the pavement.

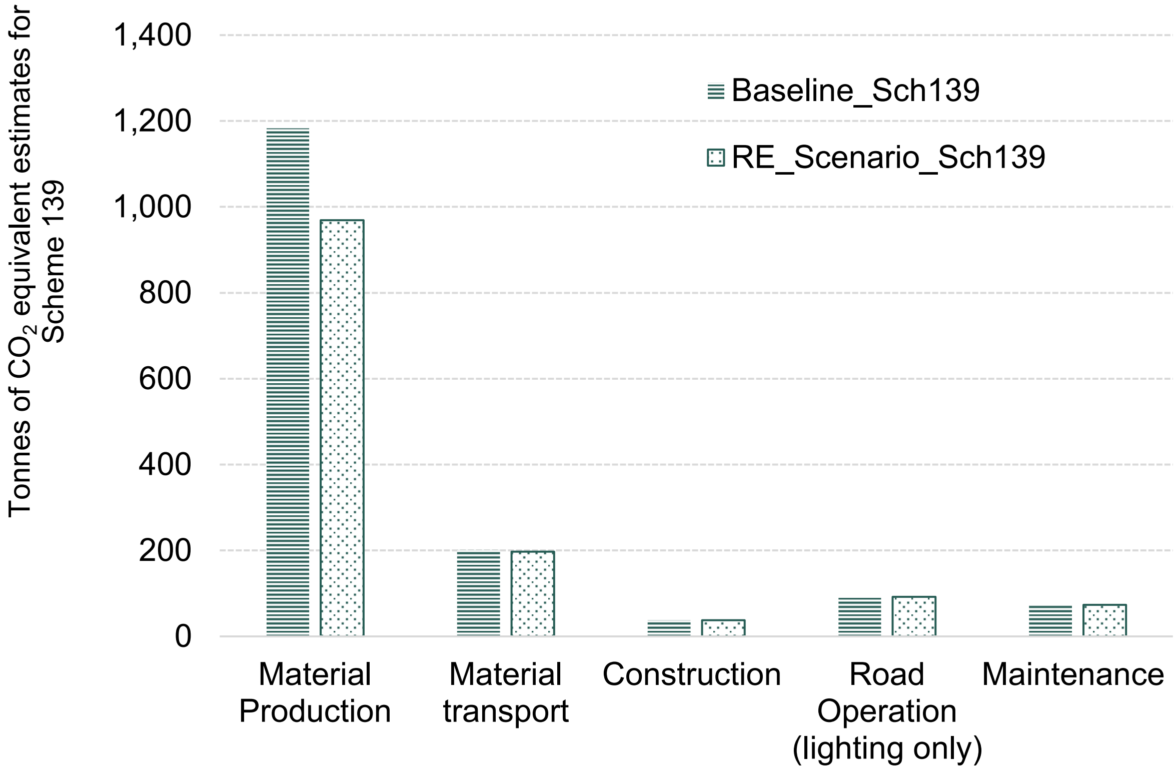

Figure 19: Embodied and Operational carbon estimated for scheme 139: Dualling of A1068 Fisher Lane

Built using conventional materials, the sensitivity of the scheme's whole life carbon to a steadily decarbonizing grid was assessed. With time and grid decarbonisation, the scheme is determined to be 5.7-7% and 6-14% more carbon-saving under the 'Steady Progression' and 'System Transformation' scenarios, compared to the baseline year 2020 (Figure 21).

With resource-efficient construction (in a 'CCS' setting), the maximum carbon saving obtainable is about 17-25% (savings of 278-411 tCO_2eq), relative to the 2020 'Steady Progression' estimates. In a 'no CCS' setting, these efficiencies become restricted to between 6.3-8% (savings of 130-235 tCO_2eq), for the conventionally constructed scheme. As for a scheme built employing resource efficiency principles, the overall carbon savings are restricted between 17-19.2% (savings of 278-306 tCO_2eq), compared to baseline. These outcomes have been presented in (Figure 20). Despite the consideration of variable scenarios encompassing carbon-negative emissions from grid decarbonisation and resource efficient construction, the capability to reach 'zero-emissions' is challenged by a large share of embodied emissions which makes up 65-74%, past the net-zero year (by 2060).

Care must be taken with the outcomes reported in this analysis since the uncertainties from real-world specifications, including changing trends in road traffic volumes, resulting asset maintenance routines, commercial innovation in infrastructure construction and maintenance, end-of-life management of recovered materials, and materialisation of the FES2020 vision, 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.

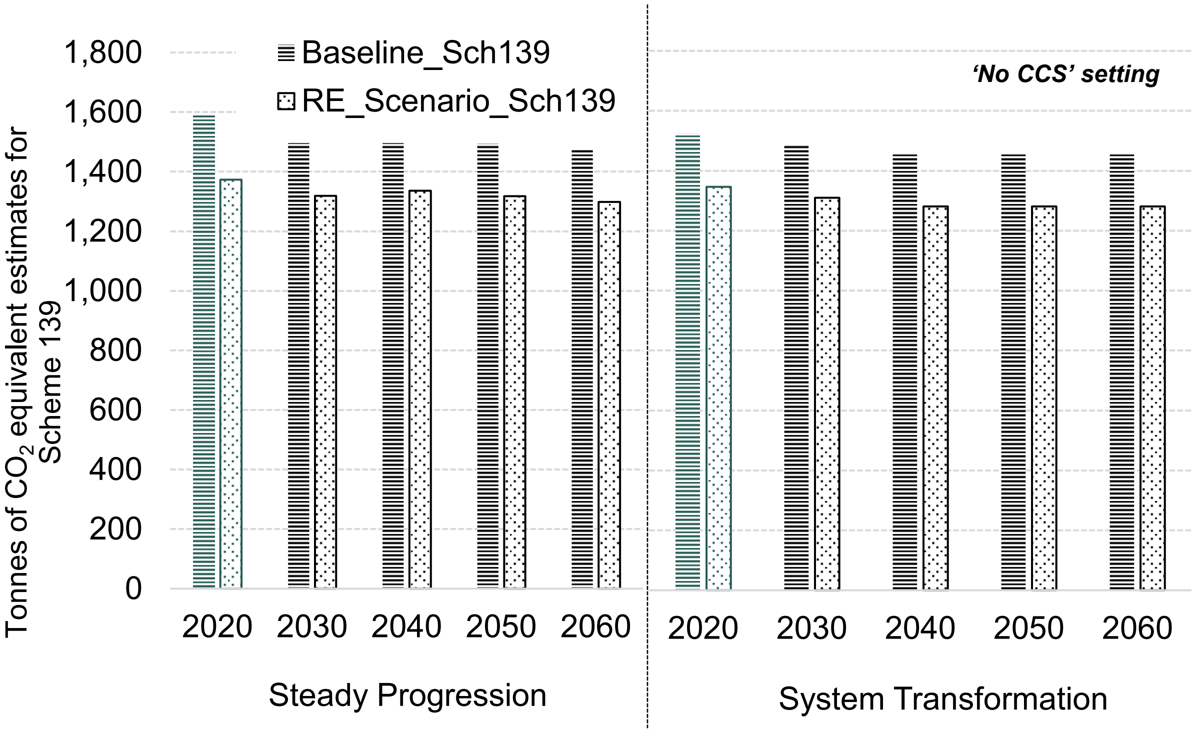

Figure 20: Whole life emissions estimated for scheme 44, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'no CCS' setting, (Baseline_Sch139: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch139: Resource Efficient build using circular and secondary materials suitable for pavement construction)

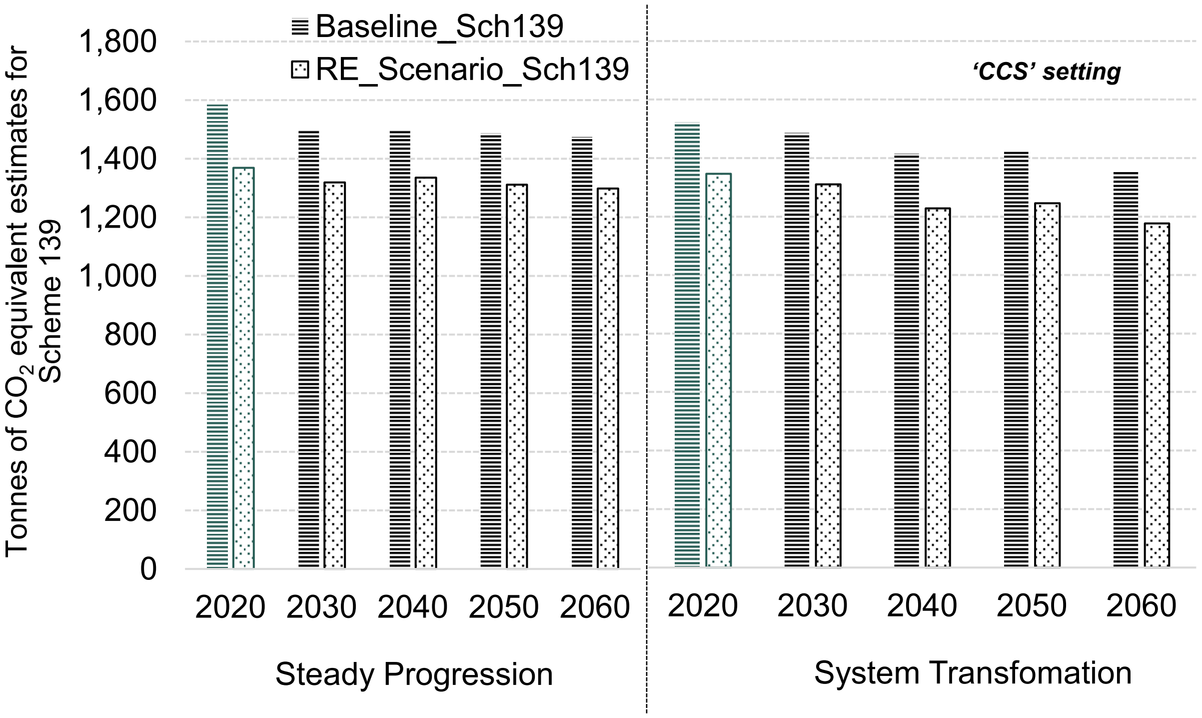

Figure 21: Whole life emissions estimated for scheme 139, applying the impacts of a steadily decarbonising grid, between 2020 and 2060, under a 'CCS' setting, (Baseline_Sch139: Conventional build using standard choice of materials meant for pavement construction; RE_Scenario_Sch139: Resource Efficient build using circular and secondary materials suitable for pavement construction)

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DecarboN8 has received funding from the EPSRC Energy Programme, grant agreement EP/S032002/1