A report on behalf of Transport Scotland and in association with Natural Capital

Forth Replacement Crossing

Sustainability Appraisal and Carbon Management Report

Appendix 6:

Energy and Carbon Report

November 2009

Contents

1 Introduction

1.1 Purpose

The purpose of this report is to provide information summarising:

- how the issue of energy and carbon is addressed using sustainability management tools;
- energy and carbon accounting;
- the estimated energy and carbon footprint of the Stage 3 design; and
- how the energy and carbon footprint will be monitored going forward against the above baseline.

1.2 Background

A key principle of the Sustainable Development Policy for the project (refer to Appendix 1) is to:

'Seek to minimise the carbon footprint of the crossing and associated network connections by consideration of the impact of its design, procurement, construction, maintenance, operation and decommissioning'

A Sustainability Appraisal Framework has been established to underpin this policy and has been used at key stages (e.g. Stage 2 Options, Stage 3 Design). The Sustainability Appraisal Framework includes two objectives (together with associated targets and indicators) that focus on carbon, these are:

Table 1: Energy and carbon related sustainability objectives, targets, and indicators

Sustainability Objectives	Target	Indicators
12. To minimise embodied energy and carbon associated with the construction of the scheme	1. Seek to minimise the embodied energy and carbon associated with key materials and their transport to site	Estimated embodied energy and carbon
		Actual embodied energy and carbon in materials, transportation and waste
	2. Minimise energy use and all carbon emissions during construction	Predicted energy requirement and CO_2 emissions
		Actual energy used and CO_2 emissions
13. To minimise carbon emissions once the bridge is opened to traffic	1. Seek to reduce CO_2 emissions from vehicles crossing the Forth at Queensferry compared with existing FRB	Predicted CO_2 emissions
	2. Minimise the energy requirements of the new bridge (once it is open to traffic) to the minimum necessary for safe operation	Predicted energy requirements
		Actual energy requirements
	3. Maximise % of required energy for the bridge (once opened to traffic) acquired from renewable sources	Predicted energy sources
		Actual energy sources

This report provides information which can be used to measure progress against objective 12, embodied energy and carbon associated with construction of the scheme.

1.3 Operational Carbon

The regional air quality assessment reported in Chapter 15 of the ES uses a standard approach to address the difference between the air quality that would be likely with the proposed scheme (the 'Do-Something' scenario) and without the proposed scheme (the 'Do-Minimum' scenario) for both the anticipated year of opening (2017) and the design year 15 years after opening (2032). The future Do-Minimum scenario assumes that the Forth Road Bridge is still in operation.

The regional assessment in the ES presents total CO_2 emissions for the road network covered in the TMfS:05a (Traffic Model for Scotland) for 2005, 2017 Do-Minimum and 2017 Do-Something scenarios as well as total distance travelled in each scenario and emissions per kilometre travelled. Using standard methodology, there is a calculated increase of 14,952 tonnes per year of CO_2 emissions between the Do-Minimum and Do-Something scenarios in 2017, which is consistent with the predicted increase in vehicle kilometres travelled along the traffic links selected for the regional air quality assessment.

This assessment of CO_2 emissions is based on traffic flows from the strategic traffic model, TMfS:05A. This approach uses established Department for Transport formulae (DMRB emission factors) to calculate CO_2 emissions based on model output speeds and volumes. This approach forecasts modest increases in CO_2 emissions, associated with the introduction of the proposed scheme.

The use of the strategic traffic model has the advantage of wide network coverage, so all of the network effects of the proposed scheme will be encompassed by the assessment. The methodology used to calculate emissions is consistent with many other road projects assessed in Scotland in recent years and it is recognised as the current best practice. However, the CO_2 calculations are based on average speeds and this approach is not capable of assessing the local impact of stop-start traffic conditions. In addition, it does not address the negative impact of the major maintenance and recabling work that would be likely to be required in the absence of a replacement crossing.

Transport Scotland recognised that a refinement to the standard methodology was required to address this matter. A new Passenger car and Heavy-duty Emission Model (PHEM) based emissions calculation module has been developed. This can be used with microsimulation models such as S-Paramics (referred to generically as Paramics). The emissions evaluation using Paramics with PHEM relationships is a technique being developed on behalf of Transport Scotland, but not yet fully approved for use in scheme appraisal. The information obtained from this evaluation tool has been used to supplement the strategic calculations which are based on the Department for Transport formulae. The PHEM based results are intended to provide a more informed view of the likely locally generated impact of the proposed scheme.

The PHEM model output is a series of emission factors, based on vehicle type, vehicle speed, vehicle loading and vehicle acceleration. This method calculates the rate of emission for each vehicle at each simulated timestep. The use of PHEM emissions relationships with the Paramics model offers the ability to take into account emissions from stop-start motoring, which is not fully reflected within the global evaluation within the air quality model which is based on traffic information from the Transport Model for Scotland (TMfS). The local PHEM based assessment therefore examines the localised effect of stop start motoring conditions on the congested approaches to the Forth Road Bridge and the localised benefits to be derived from relieving these conditions. It is recognised that this local assessment does not quantify wider impacts outwith the Paramics model area.

Traffic conditions in peak periods within the vicinity of the Forth Road Bridge are frequently congested. The established and standard methodology for calculating CO_2 emissions, (based on the Department for Transport formulae), relies on average traffic speed as the basis for calculation. In comparison to the Do-Minimum, the proposed scheme will result in smoother traffic flows and improved journey time reliability. The average speed calculated on the network, using the Department for Transport method, in the vicinity of the scheme in the

Do-Minimum scenario, reflects a range of emissions conditions from traffic which is variously accelerating, braking, idling and cruising, rather than travelling steadily at that average speed. One of the features of the Managed Crossing Scheme is that traffic will be controlled to improve flow conditions and hence, reduce emission rates, compared with the current conditions.

Tests were undertaken using the Paramics / PHEM module to compare Do-Something traffic emissions with Do-Minimum emissions in the AM and PM modelled periods for 2017 forecasts. The scheme design in conjunction with ITS operation will result in improved fuel efficiency and lower emissions per kilometre. However, the Do-Something scheme involves additional travel distance for cross Forth traffic and additional traffic demand which result in increased CO_2 emissions.

In this Do-Something scenario, the additional CO_2 emissions for the AM period are forecast to be 3.7 tonnes in the AM period and 14.7 tonnes in the PM period. These forecasts relate to AM and PM periods during average week day traffic. The proposed scheme involves some additional travel distance to cross the Forth and attracts more traffic to this part of the network. As a result of these two factors, the travel distance in terms of vehicle kilometres is expected to increase in the Do-Something scheme, compared with the Do-Minimum comparator.

Results of the test are presented in Tables 2 and 3.

Table 2: Total CO_2 Emissions within the Paramics Network in 2017 (tonnes)

Pollutant	Emissions 2017 Do-Minimum	Emissions 2017 Do-Something	Difference 2017DM/2017 Do-Something	% Change (local area) 2017 Do-Something versus 2017 Do-Minimum
CO_2 (Tonnes) AM	253.1	256.8	3.7	1.5%
CO_2 (Tonnes) PM	268.4	283.1	14.7	5.5%

Table 3: Total vehicle Kilometres within the Paramics Network in 2017

	Vehicle Kilometres 2017 Do-Minimum	Vehicle Kilometres 2017 Do-Something	Difference 2017DM/2017 Do-Something	% Change (local area) 2017 Do-Something versus 2017 Do-Minimum
AM	932,669	995,484	62,815	6.7%
PM	1,129,048	1,191,004	61,956	5.5%

If the fuel efficiency of the network operation were to remain constant, the rate of CO2 per kilometre would also be expected to remain constant. Total vehicle kilometres is the measure of total distance travelled by all vehicles in the model network. If the Do-Something model were to operate with the same level of fuel efficiency as the Do-Minimum, then we would expect the proportionate change in emissions to be similar to the increase in vehicle kilometres.

When we compare the increases in CO2 in Table 2 with the increases in vehicle kilometres in Table 3, we can see that the percentage increase in CO2 in the PM peak is similar to the percentage increase in travel in the PM peak. However, in the AM peak the percentage increase in CO2 is significantly lower than the increase in travel distance and hence, less than might otherwise be expected. The test indicates that during the congested morning peak period, the forecast increase in CO_2 emissions from the additional traffic and distance travelled is reduced by the improved scheme design and operation of ITS, which reduces congestion.

There is less congestion relief forecast in the evening peak and therefore a smaller reduction in the predicted increase in CO_2 emissions during this period.

1.3.1 Impact of Potential Cable Replacement Works

The proposed scheme will reduce or avoid the need for cable replacement and other maintenance works that are likely to be necessary to retain the Forth Road Bridge in use in the absence of a replacement crossing. These works on the Forth Road Bridge, extending over an anticipated eight year period, would have a significant impact on traffic congestion and routing and hence emissions that the air quality assessment reported. Avoiding the need for cable replacement, and the lengthy period of congested conditions associated with that work, would mean that total CO_2 emissions during the congested peak periods for the proposed scheme are likely to be reduced.

Paramics / PHEM tests were undertaken to test the impact of main cable replacement works on the Forth Road Bridge which are anticipated to require contraflow restrictions on the existing bridge for 268 weeks over 8 years between 2012 and 2019 inclusive. The traffic conditions which will prevail for much of the time if the cable replacement is undertaken will be very different from the normal Do-Minimum conditions. Stop-start traffic will occur for longer periods in more locations under this scenario. Even allowing for a significantly reduced level of demand, the reduced capacity available on the Forth Road Bridge means that the average delay to vehicles will increase by around 40 minutes per journey, compared with normal un-restricted travel.

In order to provide a comparison of the local impacts of the cable replacement works on CO_2 emissions, similar equivalent tests were undertaken by applying the same demand to the unrestricted base network. The demand applied to both networks equates to 70% of base (2008) levels of demand. Interpeak emissions have not yet been assessed. The peak period tests also do not take account of the effects of the likely increased vehicle kms and increased congestion on competing crossings and approach routes caused by diverting traffic.

The assessed annual emissions are summarised in Table 4 below and are presented as negative numbers as they represent an impact which could be avoided by building the proposed scheme.

Table 4: Indicative Cable Replacement Impact

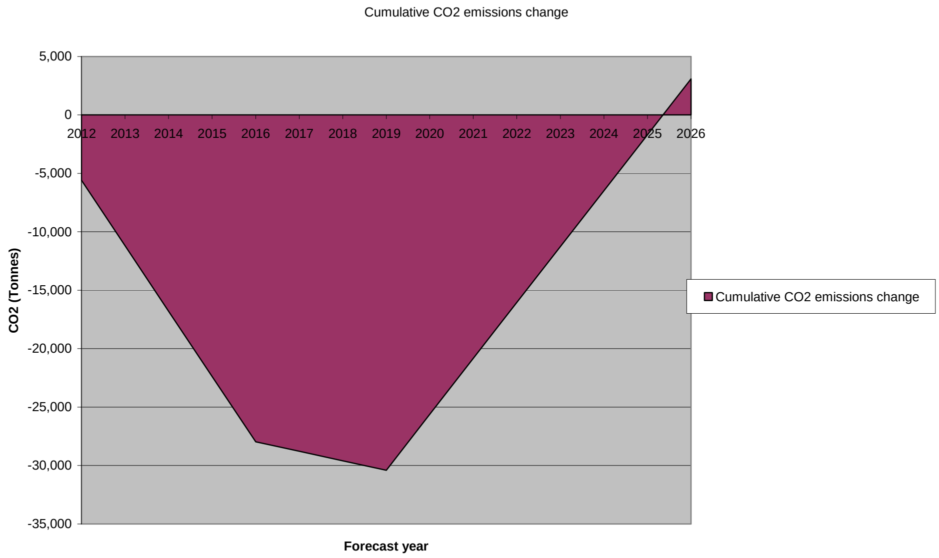
Modelled Period	Modelled CO_2(e) difference (Tonnes)	Annualisation Factor*	CO_2(e) difference per annum (Tonnes)
AM (4 hours)	-20.5	167.5	-3,434
PM(4 hours)	-12.9	167.5	-2,161
Total	-33.4		-5,595

* Annualisation Factor assumes 5 weekdays and 33.5 weeks per year.

The results in Table 4 indicate that the MCR works are likely to result in an increase in CO_2 emissions owing to an increase in congestion during the works. If the proposed scheme were implemented then this increase in emissions from the MCR works would potentially be avoided. Therefore an indication of the annual net impact of the proposed scheme on CO_2 emissions can be calculated by taking the standard assessment forecast increase in emissions owing to the proposed scheme and then subtracting the predicted local area increase in emissions that would be expected during the period of the cable replacement works.

The graph below (Figure 1) indicates the cumulative effect of the forecast changes in CO_2 emissions using this approach. As can be seen in this illustration, up to 2016, there is a net decrease in CO_2 emissions, this continues until 2019 at a lower rate as the increase in CO_2 from the proposed scheme cancels much of the reduction. After 2019 the cable replacement would be complete and hence the CO_2 emissions from the proposed scheme would now be higher than the Do-Minimum. However, there is a cumulative net saving in CO_2 emissions until 2025. Therefore the predicted increase in CO_2 emissions is delayed until 2025 by the implementation of the proposed scheme. It should be noted that the MCR impacts are derived from identical traffic demand in both the MCR modelling and the comparator Do-Minimum modelling. Therefore, only the impact of network changes are taken into account. The Managed Crossing Scheme impact, indicated in Chapter 15 (Air Quality) of the ES and presented in the graph, includes both the effect of network changes and the effect of additional traffic demand in the Do-Something scenario.

Figure 1: Indicative cumulative change in CO_2(e)



The data in Figure 1 illustrate that emissions during the congested peak periods for the proposed scheme are likely to be less than the Do-Minimum (including cable replacement) over the period 2012 to 2025. This assessment excludes the additional benefits that may result from avoiding delays and increased emissions within the interpeak periods due to cable replacement works. Further work will investigate these impacts.

1.3.2 Scheme Features to Reduce CO_2 emissions

In terms of impacts from vehicles using the crossing, the FRC scheme includes a number of features aimed at reducing CO_2 emissions. These include:

- use of Intelligent Transport Systems to improve network efficiency and decrease congestion;
- infrastructure to facilitate modal shift, particularly through the provision of a dedicated public transport corridor on the FRB and associated public transport public transport lanes and public transport links; and
- encouraging and facilitating active modes of transport (e.g. cycling) by minimising impacts on paths and cycle routes and improving these where feasible.

1.4 CEEQUAL

The Civil Engineering Environmental Quality and Awards Scheme (CEEQUAL) is an assessment and awards scheme for improving sustainability in civil engineering projects being promoted by the Institution of Civil Engineers and others. Its objective is to encourage the attainment of environmental excellence in civil engineering projects, and thus deliver improved environmental and social performance in project specification, design and construction.

The Forth Replacement Crossing is pursuing accreditation with CEEQUAL. The issue of energy and carbon forms component of the overall assessment.

1.5 Scheme Description

The FRC is a major infrastructure project comprising a new cable-stayed bridge across the Firth of Forth with associated new road connections and improved road infrastructure to the north and south. A description of the project is provided in Section 1.1.2 of the Sustainability Appraisal and Carbon Management Report. Additional detail can be found in the DMRB Stage 3 Scheme Assessment Report (Jacobs Arup 2009a) and Chapter 4 of the ES (Jacobs Arup 2009b).

2 Methodology

2.1 Introduction

The Sustainable Development Policy sets out the key sustainability principles and objectives which form a core thread throughout all the activities of the project team and stages in the project life cycle. Reducing the environmental impacts of the scheme, including lowering the carbon footprint, is integral to this policy.

An energy and carbon assessment has been established for the scheme, and this will be used as a tool for several purposes:

- for comparing scheme options;
- for driving innovation within the scheme design;
- for use in reviewing tender proposals from potential contractors; and
- for monitoring and measuring efficiencies.

2.2 Highways Agency Carbon Accounting Tool

The Highways Agency (HA) Carbon Accounting Tool (HA 2008; HA 2009) has been developed with reference to existing carbon accounting methodologies and information from the Environment Agency, Department of Environment, Food and Rural Affairs (DEFRA) and the International Organization for Standardization, and has drawn upon recognised best practice. The overall scope of the Accounting Tool is to cover all operations and activities over which HA has control, defined in terms of financial or contractual commitments for which HA is ultimately responsible. This includes responsibility for the greenhouse gas emissions produced by its supply chain when they are undertaking business on behalf of the Agency.

As such, the model can be used to capture emissions from power consumption, fuel usage, resources consumed and discarded, and the embodied energy elements associated with extraction, manufacture, production, installation, and transportation of all elements utilised on behalf of the Agency. The HA Carbon Accounting Tool (HA 2008; HA 2009) can be used to create a carbon footprint for all aspects of the FRC construction project as well as for the ongoing maintenance operations required.

2.2.1 Emissions Calculation Approach

Emissions are calculated by applying documented emission factors that convert a measure of activity from an emissions source into a volume of greenhouse gases (GHG) emissions. Emissions are reported as CO_2 (rather than CO_2e or carbon equivalent as per DEFRA guidance, refer to section 7). An example calculation is included below:

Measure of activity X Emissions Factor = Emission Estimate

100 tonnes of steel X 1.77 tCO_2/t = 177 tCO_2

Where tCO_2 = tonnes of CO_2

2.2.2 Key Data Sources

Identified below are the key published data sources referred to within the HA Carbon Accounting Tool (HA 2008; HA 2009) to provide the majority of emission factors.

- Guidelines to DEFRA's GHG Conversion Factors for Company Reporting – Annexes, (DEFRA 2007a).
- Inventory of Carbon and Energy (University of Bath 2007).

- Carbon Calculator for Construction Activities (Environment Agency 2007).

Assumptions and uncertainties are an inherent part of the carbon footprinting process as is the recognition that there are limitations in the data available. Future developments and clarifications will help to refine the assessment as the project progresses.

2.3 Inventory of Carbon and Energy

The Inventory of Carbon and Energy (ICE) Version 1.6a is the University of Bath's embodied energy and embodied carbon database, and is a freely available summary of the larger ICE-Database (University of Bath 2008). It provides an inventory of embodied energy and carbon coefficients for building materials. The data has been collected from secondary sources in the public domain (journal articles, books, conference papers, etc). The report is structured into 34 main material groups (i.e. aggregates, metals etc) with a material profile created for each main material.

The Inventory of Carbon and Energy report provide the following explanatory note, defining the term 'embodied energy':

> "*The embodied energy (carbon) of a building material can be taken as the total primary energy consumed (carbon released) over its life cycle. This would normally include (at least) extraction, manufacturing and transportation. Ideally the boundaries would be set from the extraction of raw materials (including fuels) until the end of the products lifetime (including energy from manufacture, transport, energy to manufacture capital equipment, heating and lighting of factory, maintenance, disposal…etc), known as 'Cradle-to-Gate', which includes all energy (in primary form) until the product leaves the factory gate. The final boundary condition is 'Cradle-to-Site', which includes all of the energy consumed until the product has reached the point of use (i.e. building site).*"

Boundary conditions for each material are specified within the material profiles. Cradle-to-Gate is the boundary condition most commonly specified in the report. Users are encouraged to consider the impacts of transportation for their specific case. In a few cases Cradle-to-Grave has been specified due to the original data resources.

The Inventory of Carbon and Energy contains both embodied energy and carbon data[1], but the embodied energy coefficients carry a higher accuracy. One of the main reasons for this is that the majority of the collected data was for embodied energy, not embodied carbon. Many of the embodied carbon coefficients within ICE were estimated by the authors based on the typical fuel mix in the relevant UK industries. There are, however, uncertainties associated with this method of determining embodied carbon as a result of different fuel mixes and technologies (i.e. electricity generation). For example, two factories could manufacture the same product, resulting in the same embodied energy per kilogram of product produced, but the total carbon emitted by both could vary widely dependent upon the mix of fuels consumed by the factory.

Even with the most reliable data, embodied energy and carbon analysis carries a natural level of uncertainty. The ICE database has proved to be robust when compared with other similar inventories.

2.3.1 Selection Criteria

The embodied energy and carbon coefficients selected for the ICE database were representative of typical construction materials employed in the British market. In the case of metals, the values for primary and recycled materials were first estimated, and then a

[1] The carbon coefficients contained within the ICE database are generally consistent with those in the Highways Agency Carbon Accounting Tool. Where there are discrepancies these are noted in the calculation tables.

recycling rate (and recycled content) was assumed for the metals typically used in the marketplace. This enabled an approximate value for embodied energy in industrial components to be determined.

2.3.2 Transport

Boundary conditions within the Inventory of Carbon and Energy are selected as cradle-to-gate. Transport from factory gate to construction site is not therefore included. Emissions associated with transport must be calculated separately. Section 7 considers emissions associated with transport of materials to site. The Sustainable Resource Framework also addresses material sourcing and sets targets to source materials locally where possible.

2.3.3 Recycling Methodology

The Inventory of Carbon and Energy recycling methodology is known as the recycled content approach. However, the metal industries endorse a methodology known as the substitution method. Each method is fundamentally different. The recycled content approach is a method that credits recycling, whereas the substitution method credits recyclability.

The Inventory of Carbon and Energy considers the recycled content approach most suitable for the construction industry. The substitution method may run the risk of under accounting for the full impacts of primary metal production.

2.3.4 Advisory Notes

- Functional units: It is inappropriate to compare materials solely on a kilogram basis. A comparative study should consider the quantity of materials required to provide a set function. It is only then that two materials can be compared for a set purpose.
- Lifetime: Ideally the functional unit should consider the lifetime and durability of the product.
- Waste: The quantity of waste generated from the production of materials must be considered. This should include analysis of what happens to the wasted materials, whether they are re-used, recycled or disposed of to landfill.
- Maintenance: The maintenance requirements and the impact this has on energy and material consumption needs to be considered.

3 Initial Carbon Footprint Assessment

3.1 Purpose

During DMRB Stage 2, a carbon footprinting exercise was carried out to provide a high-level comparison of the carbon emissions associated with two scheme alternatives for the proposed Forth Replacement Crossing as defined in the Scheme Definition Report (Jacobs Arup 2009g).

A brief overview of the characteristics of the two schemes is provided in Table 5 below:

Table 5: Characteristics of the two scheme alternatives

Replacement Bridge Scheme (FS2)	Managed Crossing Scheme (MG2)
• Extensive new road network and associated earthworks • Three-corridor main crossing (orthotropic cable-stayed bridge with twin concrete box girder approach viaducts) with separate provision for public transport • No refurbishment of existing Forth Road Bridge (FRB)	• Less extensive road network and associated earthworks • Two-corridor main crossing (orthotropic cable-stayed bridge with twin concrete box girder approach viaducts) with no separate provision for public transport • Refurbishment of FRB to allow use by public transport

3.2 Limitations

The components of the scheme alternatives that were included in the carbon assessment were limited to those that could be reasonably estimated at that stage of the project. Included in this early assessment were estimates of the types and amounts of construction materials to be used in the new road network, main crossing and refurbishment of the Forth Road Bridge (for MG2 only). However, it was not possible at Stage 2 to include:

- accurate estimates of the likely energy required for other aspects of the construction such as the use of plant and equipment or the removal of waste from site; and
- emissions associated with the operation of the Forth Replacement Crossing i.e. vehicle usage and bridge maintenance.

3.3 Methodology and Scope

The carbon footprint assessment was based on the information contained in the Highways Agency (HA) Carbon Accounting Tool for Major Projects (HA 2009). The HA model is described in Section 2.2 above.

The carbon footprint assessment for the two scheme alternatives was initially limited to the construction materials to be used in the schemes.

At Stage 3, the scope of the assessment was widened to include other aspects such as energy use, transportation of materials, waste generation. This assessment is presented from Section 4 onwards.

3.4 Presentation of Results

3.4.1 Data Gathering and Key Assumptions

(a) Road Network

(i) Option FS2

Pavement = 487,000 m^2 of new construction and 148,000 m^2 of overlay/inlay
Earthworks cut = 1,159,000 m^3 and fill = 2,700,000 m^3

(ii) Option MG2

Pavement = 254,000 m^2 of new construction and 254,000 m^2 of overlay/inlay
Earthworks cut = 628,000 m^3 and fill = 340,000 m^3.

(b) Main Crossing

(i) Option FS2

Three-corridor main crossing (orthotropic cable-stayed bridge with twin concrete box girder approach viaducts) with separate provision for public transport.

(ii) Option MG2

Two-corridor main crossing (orthotropic cable-stayed bridge with twin concrete box girder approach viaducts) with no separate provision for public transport.

(c) Future Refurbishment of existing Forth Road Bridge

Option MG2 only:

- Ready mix concrete: high strength = 588 tonnes
- Steel: general = 1,595 tonnes
- Asphalt = 388 tonnes

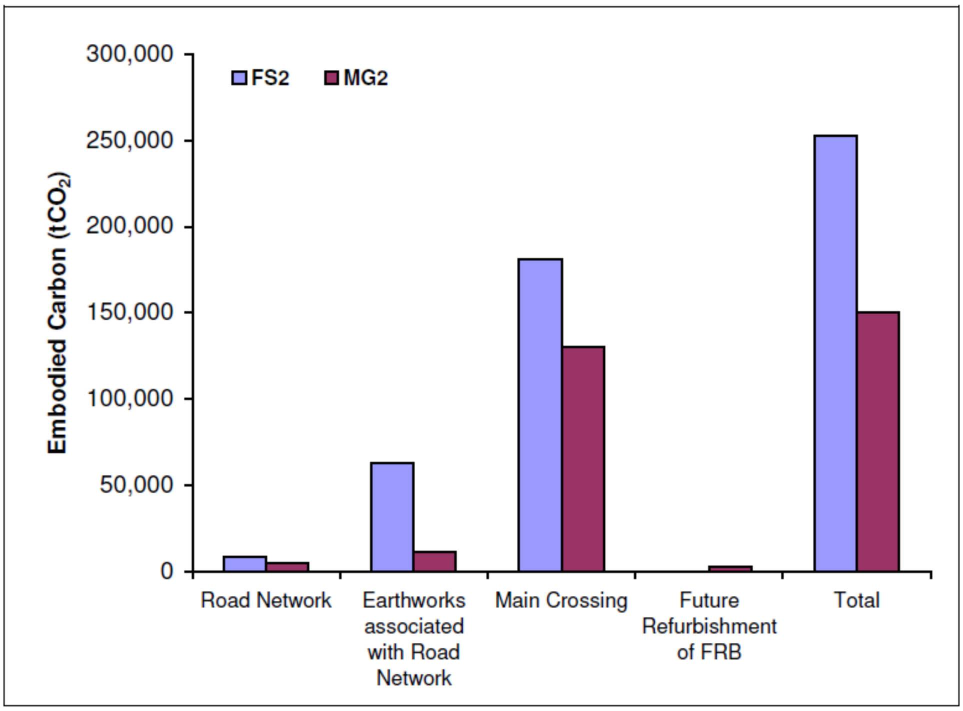
3.4.2 Results

A summary of the results of the initial carbon footprinting exercise is provided in Table 6 and Figure 2 below:

Table 6: Summary carbon footprinting results comparing two scheme alternatives

Component	Embodied Carbon (tCO_2)			
	FS2		MG2	
	tonnes CO_2	Proportion of Scheme Carbon Footprint	Tonnes CO_2	Proportion of Scheme Carbon Footprint
Road Network (main materials i.e. asphalt & aggregate to be used in construction of new pavement and overlay/inlay of existing pavement)	8,575	3%	5,029	3%
Earthworks associated with Road Network	62,873	25%	11,750	8%
Main Crossing (Orthotropic Cable-Stayed Bridge & Twin Concrete Box Girder Approach Viaducts)	180,947	72%	130,312	87%
Refurbishment of Existing FRB (main materials i.e. steel concrete & asphalt) to be used in refurbishment	0	0%	3,028	2%
TOTAL	**252,395**		**150,119**	

Figure 2: Summary carbon footprinting results comparing two scheme alternatives



Based on this analysis, it was calculated that Option FS2 would result in approximately 68% (102,000 tonnes) more embodied carbon than Option MG2:

- for both options the Main Crossing represents the greatest proportion of the embodied carbon. The embodied carbon associated with the Main Crossing for FS2 is approximately 39% (52,000 tonnes) more than for MG2;
- FS2 would entail more earthworks than for MG2 and this is reflected in the difference (approximately 51,000 tonnes) in embodied carbon for this component; and
- the future refurbishment of the FRB (Option MG2) represents a very small proportion of embodied carbon (approximately 2%).

3.4.3 Sourcing Scenarios

Table 7 provides an illustration of how the different materials that would be used in the two FRC scheme alternatives contribute to their respective carbon footprint:

Table 7: Breakdown of carbon footprint by material type

Component	Proportion of Carbon Footprint	
	FS2 – Replacement Bridge Scheme	MG2 – Managed Crossing Scheme
Steel	48%	65%
Soil requiring import/export (earthworks)	30%	8%
Concrete	16%	22%
Asphalt	3%	1%
Quarried aggregate	2%	1%
Polymer membrane	1%	1%

From the above it can be seen that steel and concrete contribute the majority of the embodied carbon associated with construction materials to be used in either scheme, and that the earthworks, especially those associated with FS2, are also a major contributor. As such it is considered that the greatest potential "savings" in terms of the carbon emissions associated with the construction materials to be used in the project, irrespective of which scheme alternative is selected, will be made by concentrating on these key areas i.e. seeking out alternative materials or crossing designs that would use these key materials more efficiently.

In addition, some simple calculations have been carried out using the available data in order to illustrate how different sourcing scenarios would affect the carbon footprint of the crossing. For example, it has been calculated that:

- sourcing all the steel locally rather than from further afield, could represent a carbon "saving" of over 6,000 CO_2 on the transportation of that steel to site (approximately 2.6% of the overall footprint for FS2); and
- using 100% recycled aggregate rather than using 100% freshly quarried aggregate could represent a savings of nearly 2,000 tonnes CO_2 (approximately 0.75% of the overall footprint of FS2).

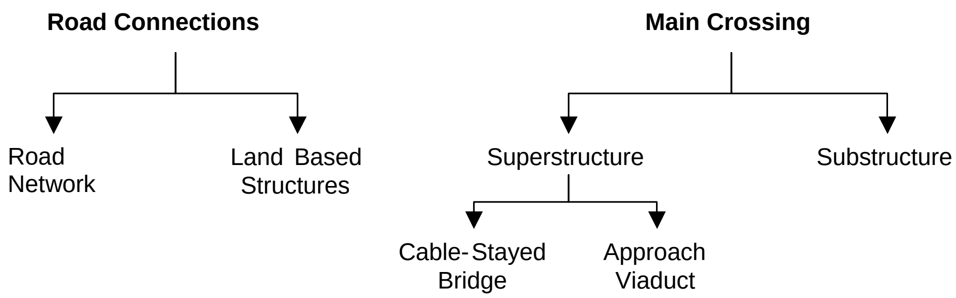
4 Embodied Energy and Carbon at Stage 3 Design

4.1 Introduction

Building on the high-level carbon footprinting exercise carried out at the initial design stage, a more detailed analysis was carried out as the design developed. This assessed the embodied energy and carbon associated with key materials and components to be used in the scheme. The analysis is based on energy and carbon coefficients extracted from the Inventory of Carbon and Energy database (University of Bath 2008) and the HA Carbon Accounting Tool (HA 2008; HA 2009). Annex A provides an inventory of energy and carbon coefficients used in the assessment.

The energy and carbon assessment divides the scheme into its main component parts, as shown in Figure 3. Material quantities were provided by each of the relevant design teams. This assessment is based on Stage 3 Design.

Figure 3: Main Component of the FRC scheme



4.2 Road Connections

4.2.1 Roads Network

Table 8 presents a summary of embodied energy and carbon associated with materials to be used in the road network. These calculations are based on estimated material quantities and the application of appropriate energy and carbon values to give total embodied energy and carbon (details of energy and carbon factors are provided in Annex A).

Material quantities are based on Stage 3 Design. This assessment includes the use of asphalt material, quarried aggregates and the import of suitable fill material. Filter materials in drains (consisting of plastic pipes of varying diameters and filter stone) have not been included as material quantities are not available at this stage.

The energy and carbon assessment for the road network has been broken down into a number of components: the pavement; overlay; sub-base; capping, and fill material. The pavement and overlay consist of asphalt material, while the sub-base and capping is made up of aggregate material. Imported fill material consists of general aggregate material.

The total embodied energy associated with these materials is 342,794 GJ and the total embodied carbon is 8,701 tCO_2. As shown in Table 8 the pavement accounts for approximately 67% of total embodied energy. The import of fill material makes up around 20%, the overlay around 8%, while the sub-base and capping account for 2% and 3% of the total respectively. Similarly, as shown in Figure 4, in terms of embodied carbon the pavement accounts for 46% of the total, the import of fill material 40%, the overlay 6%, and the sub-base and capping make up 3% and 6% respectively.

Table 8: Summary of the estimated embodied energy and carbon for road network

Component	Category	Material	Energy	Carbon
			GJ	tCO_2
Pavement	Quarry Sourced Material	General Asphalt	230,752	3,994
Overlay		General Asphalt	27,381	474
Sub-base		General Aggregate	5,221	261
Capping		General Aggregate	10,441	2,993
Import of fill		General Aggregate	69,000	3,450
		Total	**342,794**	**8,701**

Figure 4: Percentage of embodied energy by component for road network

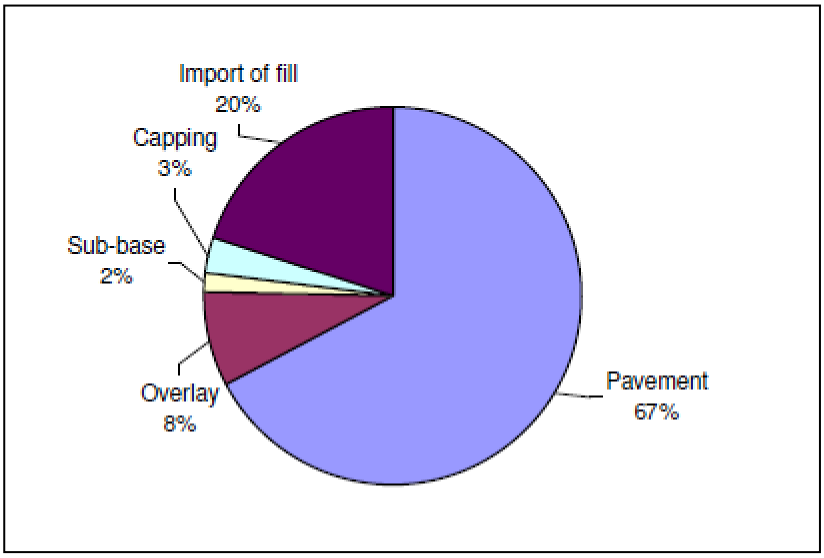
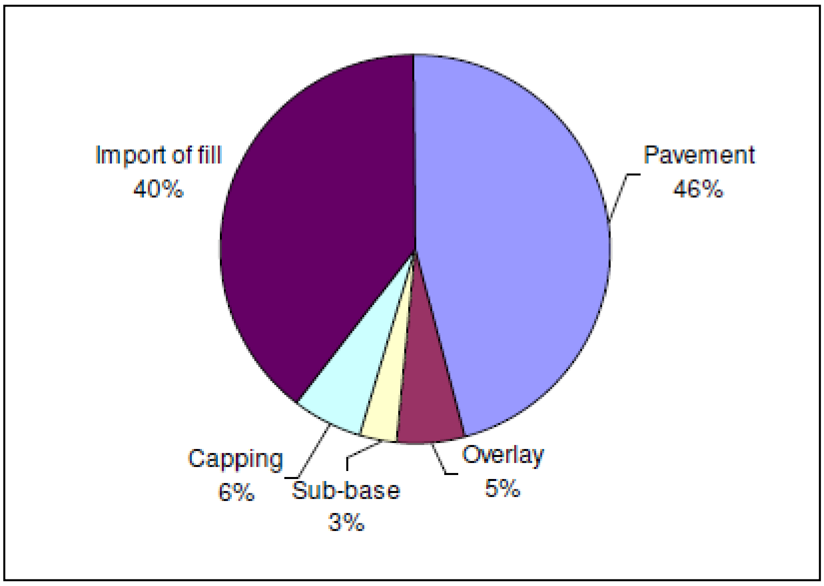


Figure 5: Percentage of embodied carbon by component for road network



4.2.2 Land-Based Structures

Table 9 below gives a summary of embodied energy and carbon associated with materials to be used in the land-based structures. As before, the energy and carbon assessment is based on estimated material quantities and the application of appropriate energy and carbon values to give total embodied energy and carbon.

The assessment includes key materials associated with construction (i.e. concrete, steel, imported fill). Material quantities are based on Stage 3 Design.

The total embodied energy associated with materials to be used in the land-based structures is 536,890 GJ, and the total embodied carbon is 47,768 tCO_2. As shown in Figure 6, steel accounts for approximately 70% of the total embodied energy, while concrete and imported fill make up around 25% and 5% respectively. In terms of embodied carbon, as shown in Figure 7, steel accounts for 54% of the total, while concrete and imported fill make up around 43% and 3% respectively.

Table 9: Summary of the estimated embodied energy and carbon for land-based structures

Category	Material	Energy	Carbon
		GJ	tCO_2
Concrete	Concrete: high strength	133,957	20,142
	Precast concrete	1,754	189
Metals	Steel: bar & rod	193,036	13,418
	Steel: section	179,883	12,606
Quarry Sourced Materials	General aggregate: Imported Fill	28,260	1,413
	Total	**536,890**	**47,768**

Figure 6: Percentage of embodied energy in land-based structures by material type

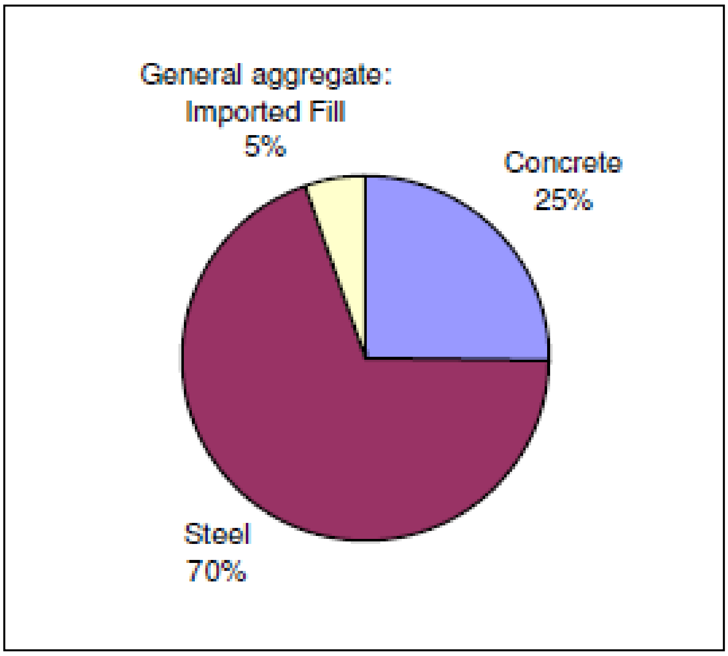
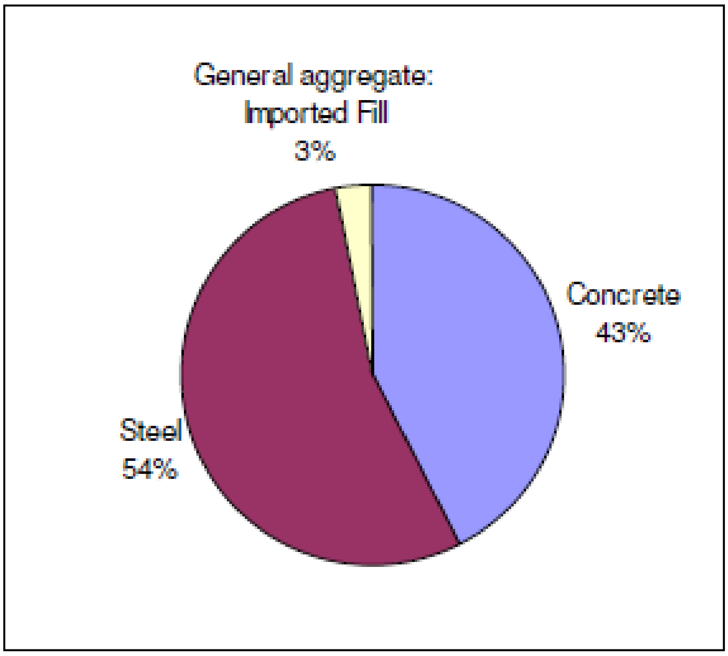


Figure 7: Percentage of embodied carbon in land-based structures by material type



4.3 Main Crossing

4.3.1 Substructure

Table 10 below gives a summary of embodied energy and carbon associated with materials to be used in the substructure of the Main Crossing. The energy and carbon assessment is based on estimated material quantities and the application of appropriate energy and carbon values to give total embodied energy and carbon.

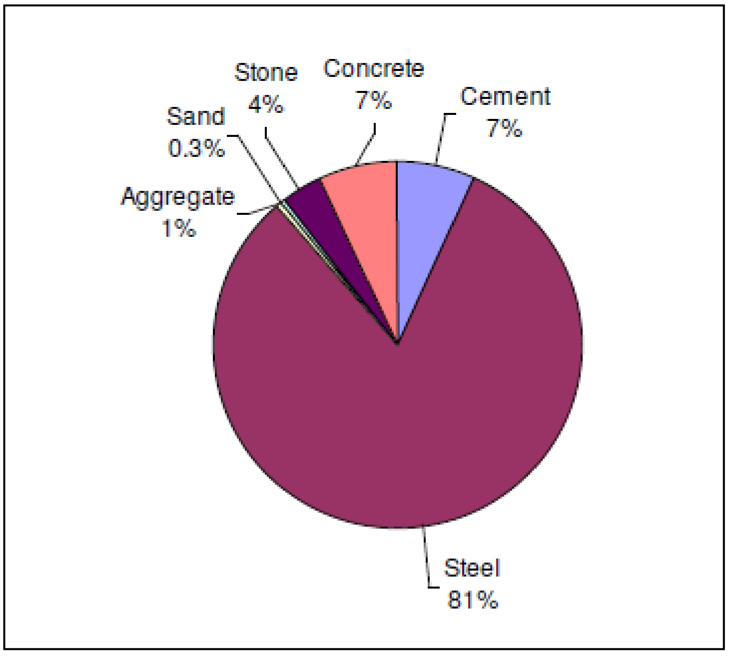
The assessment includes key materials associated with construction (i.e. cement, steel, aggregate, sand, stone, and concrete). Material quantities are based on Stage 3 Design.

The total embodied energy associated with materials to be used in the substructure is 742,986 GJ, and the total embodied carbon is 56,448 tCO_2. As shown in Figure 8 steel accounts for approximately 81% of the total embodied energy. Cement and concrete contribute around 7% each, while aggregate material, stone and sand account for the remaining 5%. As shown in Figure 9 steel accounts for around 72% of total embodied carbon, while cement makes up 14% and concrete 10%. Stone, sand, and aggregate material account for the remaining 4%.

Table 10: Summary of the estimated embodied energy and carbon for the substructure

Category	Material	Energy	Carbon
		GJ	tCO_2
Cements	Cement: general - 50% blast furnace slag	52,260	7,813
Metals	Steel: general[1]	397,410	25,791
	Sheet piling: heavy use	208,986	15,160
Quarry Sourced Materials	Quarried aggregate	3,726	298
	Recycled aggregate	582	34
	Sand	2,264	113
	Stone: general	27,060	1,515
Concrete	General Road and Pavement	39,614	4,057
	High Strength	11,084	1,667
	Total	**742,986**	**56,448**

Figure 8: Percentage of embodied energy in substructure by material type



[1] It should be noted here that it is assumed that 50% of "Steel: General" material comes from secondary (i.e. recycled) sources.

Figure 9: Percentage of embodied carbon in substructure by material type

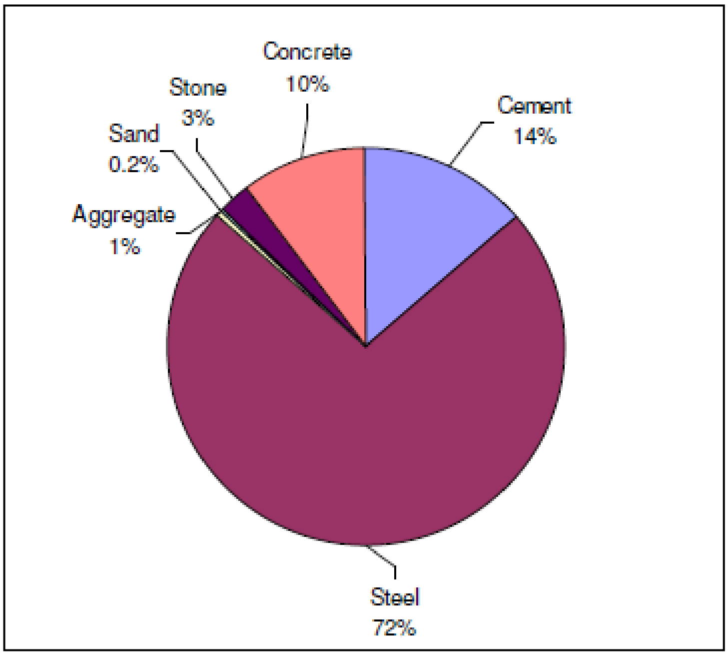


Table 11 shows the labelling scheme for each element of the Main Crossing substructure. Table 12 shows embodied energy and carbon associated with each element of the substructure. SNTBP accounts for approximately 43% of total embodied energy, while ASC (Piled) and STP account for 28% and 10% respectively.

Table 11: Labelling of elements associated with the substructure

SNTBP	South and north tower bases	ASLPr	Approach span piers, S3 to S8 and N3
STP	South tower piles	ASMPr	Approach span piers, S1, S2, N1 and N2
NTP	North tower piles	ACS (Piled)	S1, S2, S3, S4, N1 pile caps and piles
CTB	Central tower base	ACS (Pad)	S5 to S8 and N2, pads

Table 12: Estimated embodied energy and carbon associated with each component of substructure

Structure	Embodied Energy GJ	Percentage of Total	Embodied Carbon (tCO_2)	Percentage of Total
SNTBP	320,019	43%	23,701	42%
STP	76,074	10%	5,962	11%
NTP	61,815	8%	4,864	9%
CTB	33,585	5%	3,807	7%
ASC (Piled)	208,318	28%	14,408	25%
ASC (Pad)	16,557	2%	1,363	2%
ASMPr	11,151	2%	978	2%
ASLPr	15,467	2%	1,364	2%
Total	**742,986**	**100%**	**56,448**	**100%**

4.3.2 Superstructure

(a) Cable-Stayed Bridge Options

Table 13 and Table 14 present a summary of embodied energy and carbon associated with materials to be used in each of the options for the cable-stayed bridge. These calculations are based on estimated material quantities and the application of appropriate energy and carbon values to calculate total embodied energy and carbon. Details of energy and carbon factors are provided in Annex A.

The assessment includes key materials associated with construction (i.e. steel, concrete, asphalt, etc). Material quantities are based on Stage 3 Design.

The total embodied energy associated with materials to be used in the cable-stayed bridge - orthotropic is 1,257,089 GJ, and the total embodied carbon is 98,491 tCO_2. As shown in Figure 10, steel accounts for approximately 92% of the total embodied energy, while concrete accounts for about 6% of the total. As shown in Figure 11 steel accounts for approximately 89% of the total embodied carbon, while concrete accounts for about 11%.

In comparison, the total embodied energy associated with materials to be used in the cable-stayed bridge - composite is 1,215,501 GJ, and the total embodied carbon is 100,044 tCO_2. As shown in Figure 12 steel accounts for approximately 85% of the total embodied energy, while concrete accounts for about 12% of the total. As shown in Figure 13, steel accounts for approximately 78% of the total embodied carbon, while concrete accounts for about 21%.

Table 13: Estimated embodied energy and carbon for cable-stayed bridge - Orthotropic

Cable-Stayed Bridge - Single Deck Box Girder - Orthotropic			
Category	**Material**	**Energy**	**Carbon**
		GJ	**tCO_2**
Metals	Steel: general (UK typical)	839,641	60,908
	Steel: general (primary)	1,723	134
	Steel: bar & rod (UK Typical)	115,915	8,058
	Steel: bar & rod (Primary)	2,184	161
	Steel: wire	133,956	10,530
	Stainless steel	65,545	7,109
Misc	Paint	5,465	286
Quarry Sourced Materials	Asphalt	19,752	342
Concrete	Concrete (high strength)	72,908	10,962
	Concrete (general road and pavement)	0	0
	Total	**1,257,089**	**98,491**

Figure 10: Percentage of embodied energy in cable-stayed bridge by material type – orthotropic

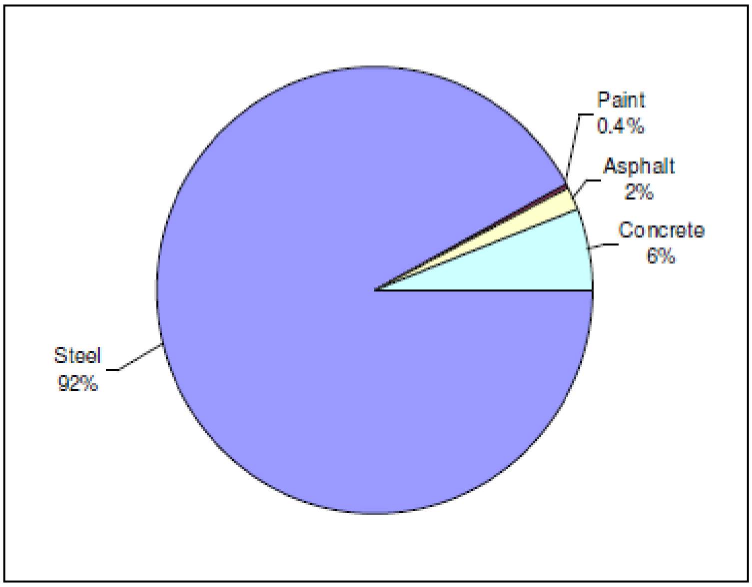


Figure 11: Percentage of embodied carbon in cable-stayed bridge by material type – orthotropic

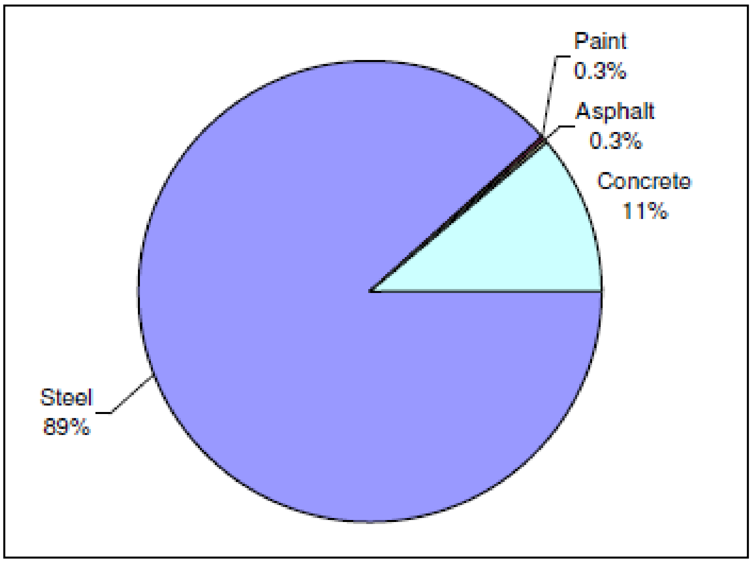


Table 14: Estimated embodied energy and carbon for cable-stayed bridge - composite

Cable-Stayed Bridge - Single Deck Box Girder - Composite			
Category	**Material**	**Energy**	**Carbon**
		GJ	**tCO_2**
Metals	Steel: general (UK typical)	571,607	41,465
	Steel: general (primary)	1,757	137
	Steel: bar & rod (UK Typical)	204,844	14,239
	Steel: bar & rod (Primary)	2,184	161
	Steel: wire	193,572	15,217
	Stainless steel	65,545	7,109
Misc	Paint	3,953	207
Quarry Sourced Materials	Asphalt	32,224	558
Concrete	Concrete (high strength)	138,327	20,799
	Concrete (general road and pavement)	1,488	152
	Total	**1,215,501**	**100,044**

Figure 12: Percentage of embodied energy in cable-stayed bridge by material type - composite

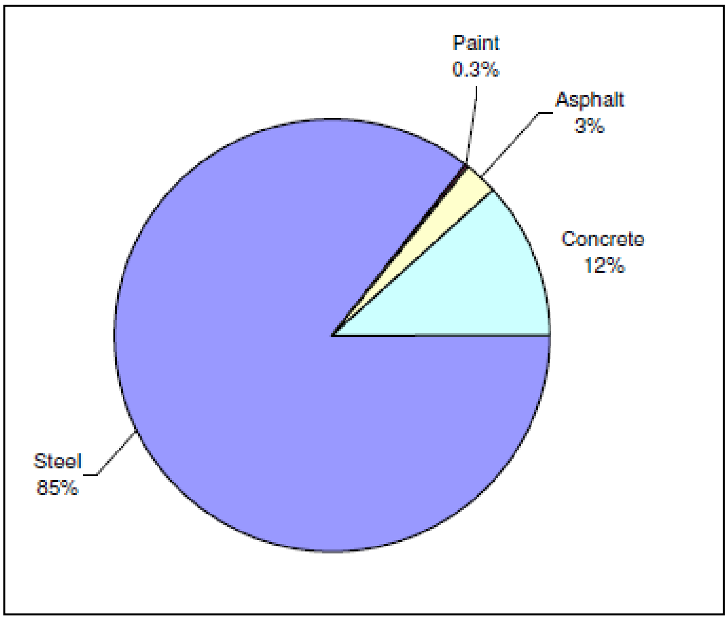
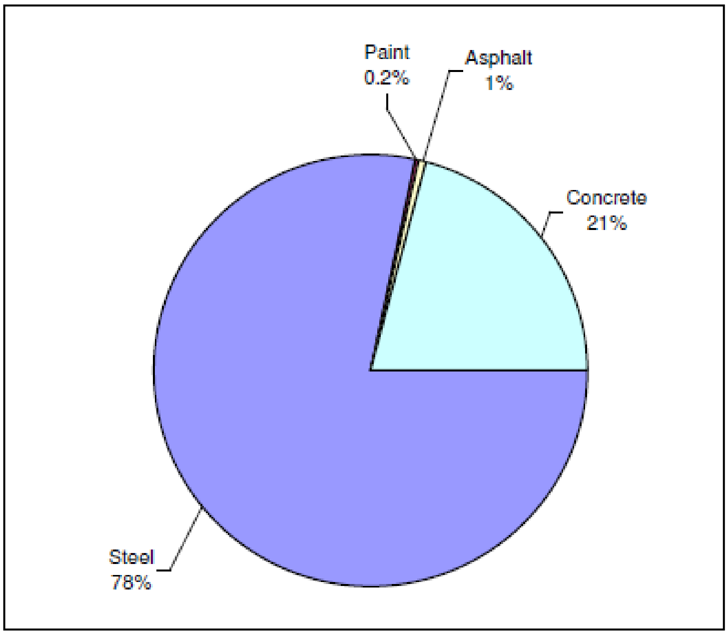


Figure 13: Percentage of embodied carbon in cable-stayed bridge by material type – composite



(b) Approach Viaduct Options

Table 15 and Table 16 present a summary of embodied energy and carbon associated with materials to be used in each of the options for the approach viaducts. As before, these calculations are based on estimated material quantities and the application of appropriate energy and carbon values to give total embodied energy and carbon.

The assessment includes key materials associated with construction (i.e. steel, concrete, asphalt, etc). Material quantities are based on Stage 3 Design.

The total embodied energy associated with materials to be used in the approach viaduct-composite is 249,815 GJ, and the total embodied carbon is 20,666 tCO_2. As shown in Figure 14 steel accounts for approximately 83% of the total embodied energy, while concrete accounts for about 14% of the total. As shown in Figure 15 steel accounts for approximately 73% of the total embodied carbon, while concrete accounts for about 26%.

In comparison, the total embodied energy associated with materials to be used in the approach viaduct - concrete is 219,265 GJ, and the total embodied carbon is 20,588 tCO_2. As shown in Figure 16 steel accounts for approximately 68% of the total embodied energy, while concrete accounts for about 28% of the total. As shown in Figure 17 steel accounts for approximately 54% of the total embodied carbon, while concrete accounts for about 45%.

Table 15: Estimated embodied energy and carbon for approach viaduct - composite

Approach Bridge - Twin Composite Box Girder			
Category	**Material**	**Energy**	**Carbon**
		GJ	**tCO_2**
Metals	Steel: general (UK Typical	134,479	9,755
	Steel: general (UK Primary)	1,271	99
	Steel: bar & rod	57,807	4,018
	Steel: wire	0	0
	Stainless steel	12,315	1,336
Misc	Paint	699	37
Quarry Sourced Materials	Asphalt	8,046	139
Concrete	Concrete (high strength)	34,979	5,259
	Concrete (general road and pavement)	218	22
	Total	**249,815**	**20,666**

Figure 14: Percentage of embodied energy in approach viaduct by material type - composite

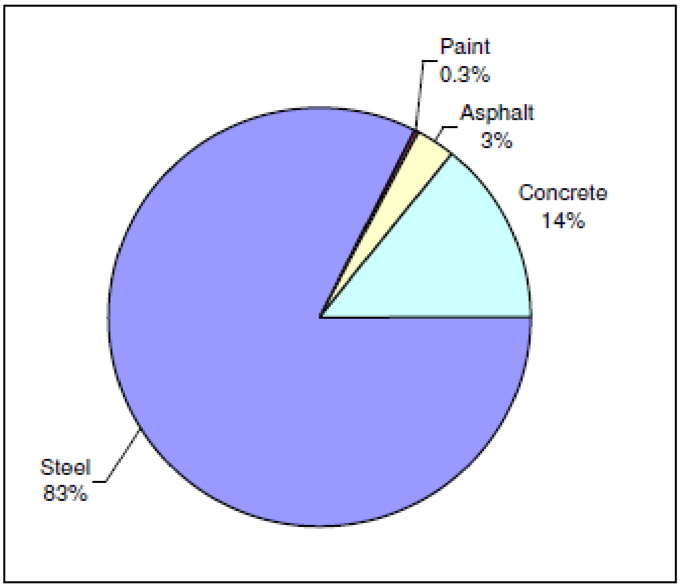


Figure 15: Percentage of embodied carbon in approach viaduct by material type – composite

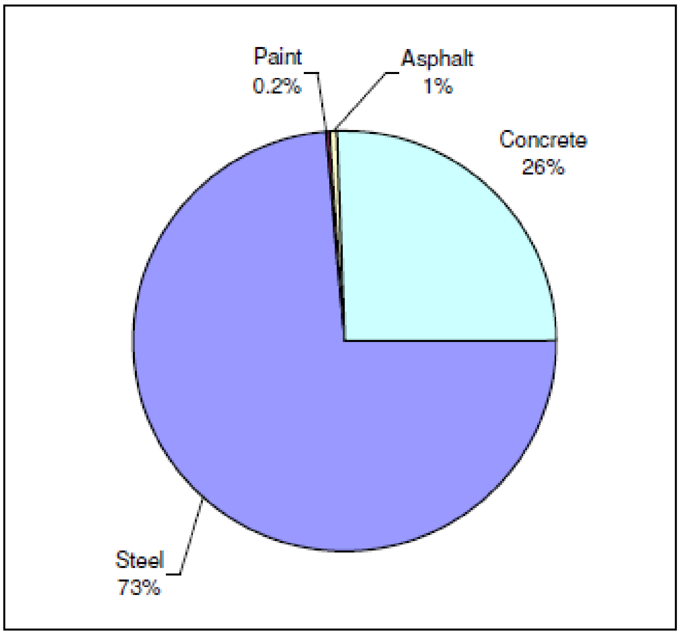


Table 16: Estimated embodied energy and carbon for approach viaduct - concrete

Approach Bridge - Twin Concrete Box Girder			
Category	**Material**	**Energy**	**Carbon**
		GJ	**tCO_2**
Metals	Steel: general (UK Typical	27,650	2,006
	Steel: general (UK Primary)	1,359	106
	Steel: bar & rod	85,482	5,942
	Steel: wire	23,030	1,810
	Stainless steel	12,315	1,336
Quarry Sourced Materials	Asphalt	8,046	139
Concrete	Concrete (high strength)	61,164	9,197
	Concrete (general road and pavement)	218	22
	Total	**219,265**	**20,558**

Figure 16: Percentage of embodied energy in approach viaduct by material type - concrete

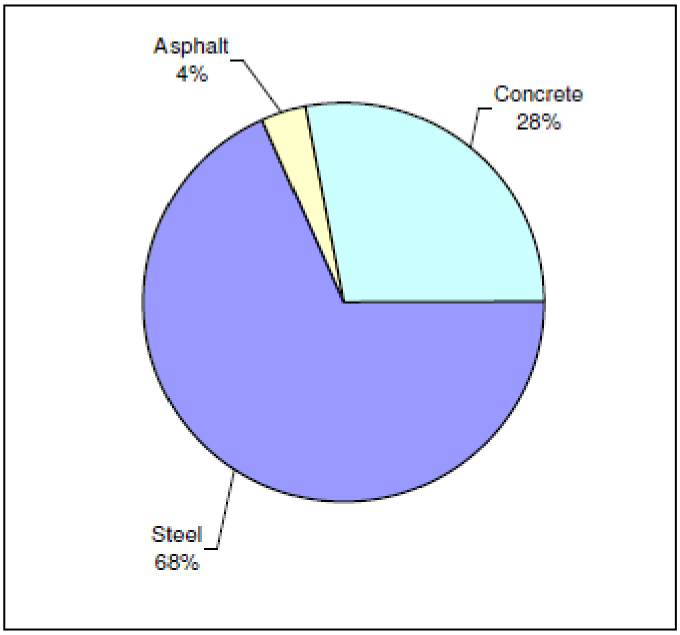
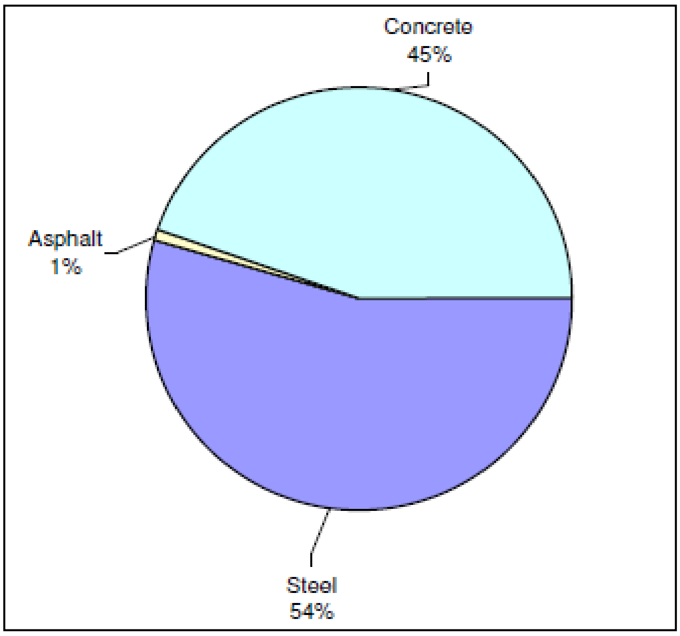


Figure 17: Percentage of embodied carbon in approach viaduct by material type - concrete



4.4 Combination of Options for Main Crossing Superstructure

Table 17 and Table 18 present a summary of embodied energy and carbon associated with potential options for the Main Crossing superstructure. In terms of embodied energy, option 1 is highest with a total embodied energy of 1,506,904 GJ. Option 4 would have the lowest embodied energy, 1,434,766 GJ. The difference between highest and lowest is 72,138 GJ, or approximately 5%.

In terms of embodied carbon, option 2 is highest with a total embodied carbon of 120,710 tCO_2. Option 3 would have the lowest embodied carbon, 119,049 tCO_2. The difference between highest and lowest is 1,661 tCO_2, or approximately 1.4% which is considered to be minimal.

Table 17: Summary of estimated embodied energy associated with combination of options for the main crossing superstructure

		Cable-Stayed Bridge	
		Orthotropic	Composite
		Embodied Energy (GJ)	
Approach Viaduct	Composite	Option 1) 1,506,904	Option 2) 1,465,316
	Concrete	Option 3) 1,476,353	Option 4) 1,434,766

Table 18: Summary of estimated embodied carbon associated with combination of options for the main crossing superstructure

		Cable-Stayed Bridge	
		Orthotropic	Composite
		Embodied Carbon (tCO_2)	
Approach Viaduct	Composite	Option 1) 119,157	Option 2) 120,710
	Concrete	Option 3) 119,049	Option 4) 120,602

4.5 Embodied Energy and Carbon Summary

Table 19 provides a summary of total embodied energy and carbon for each component of the scheme. In the case where Option 1 is chosen for the Main Crossing superstructure, the total embodied energy for the scheme would be 3,129,574 GJ and the total embodied carbon would be 232,074 tCO_2.

The Main Crossing superstructure (cable-stayed bridge and approach viaduct) makes up the greatest proportion of total embodied energy and carbon. In the case where Option 1 above is chosen, the main crossing superstructure would account for approximately 48% of the overall embodied energy of the scheme. Under this scenario, the main crossing substructure would account for around 24% of total embodied energy, while land-based structures and the road network would make up 17% and 11% respectively.

Figure 18 provides a summary of total embodied energy for each component of the scheme, with Option 1 selected for the superstructure. Similarly, Figure 18 provides a summary of total embodied carbon for each component of the scheme.

Table 19: Summary of the estimated total embodied energy and carbon for each component of the scheme

Component		Energy	Carbon
		GJ	tCO_2
Road Network		342,794	8,701
Land-Based Structures		536,890	47,768
Main Crossing Substructure		742,986	56,448
Main Crossing Superstructure	Option 1	1,506,904	119,157
	Option 2	1,465,316	120,710
	Option 3	1,476,353	119,049
	Option 4	1,434,766	120,602

Figure 18: Summary of the estimated total embodied energy and for each component of the scheme (under option 1 for main crossing)

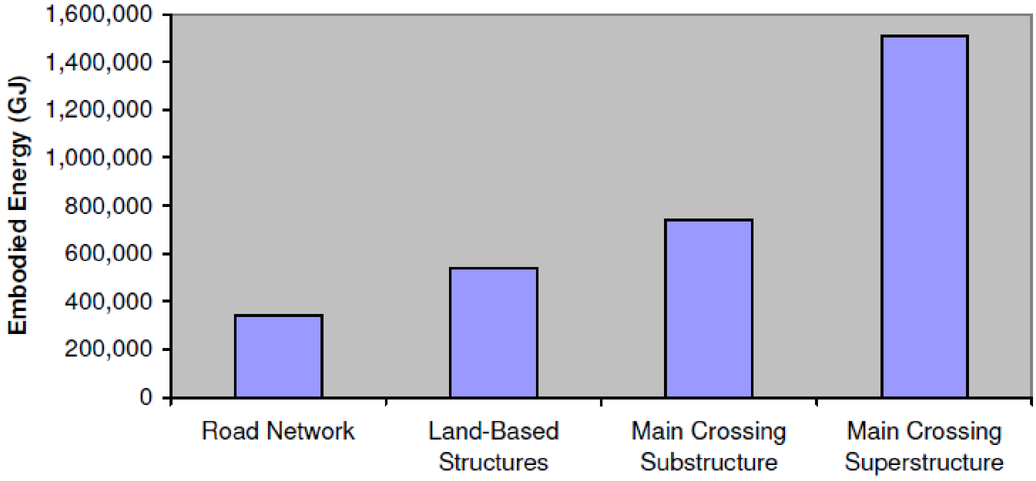


Figure 19: Summary of the estimated total embodied carbon and for each component of the scheme (under option 1 for main crossing superstructure)

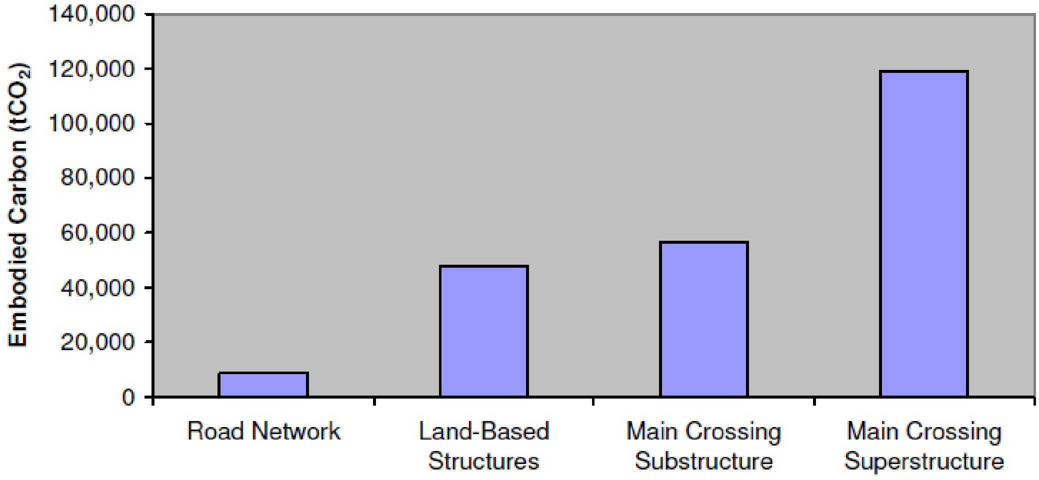


Table 20 and Table 21 below give a summary of embodied energy and carbon broken down by material type for each component of the scheme. In the case where Option 1 is chosen for the main crossing superstructure, steel accounts for approximately 75% of total embodied energy. Quarry sourced materials (aggregates, stone, asphalt, etc) make up around 14% of total embodied energy, while cement and concrete account for around 11% and paint accounts for less than 1% of the total.

In terms of carbon, again assuming Option 1 is chosen, steel accounts for approximately 73% of total embodied carbon. Quarry sourced materials make up around 5% of total embodied carbon, while cement and concrete account for around 22% and paint accounts for less than 1% of the total.

Table 20: Summary of the estimated embodied energy by material type for each component of the scheme

Category	Material Type	Embodied Energy (GJ)						
		Road Network	Structures	Substructure	Main Crossing			
					Option 1	Option 2	Option 3	Option 4
Cement	Cement: general - 50% blast furnace slag			52,260				
Metals	Steel: general (UK typical)			397,410	974,120	706,086	867,291	599,257
	Steel: general (primary)				2,993	3,027	3,082	3,116
	Steel: bar & rod (UK Typical)		193,036		173,722	262,651	201,397	290,326
	Steel: bar & rod (Primary)				2,184	2,184	2,184	2,184
	Steel: section		179,883					
	Steel: wire				133,956	193,572	156,986	216,602
	Steel: stainless				77,860	77,860	77,860	77,860
	Sheet piling: heavy use			208,986				
Misc	Paint (Average)				6,165	4,652	5,465	3,953
Quarry Sourced Materials	Quarried aggregate			3,726				
	Recycled aggregate			582				
	General aggregate	84,662	28,260					
	Asphalt	258,132			27,798	40,271	27,798	40,271
	Sand			2,264				
	Stone: general			27,060				
Concrete	General Road and Pavement			39,614	218	1,706	218	1,706
	High Strength		133,957	11,084	107,888	173,307	134,072	199,491
	Prefabricated Concrete		1,754					
	Total	**342,794**	**536,890**	**742,986**	**1,506,904**	**1,465,316**	**1,476,353**	**1,434,766**

Table 21: Summary of the estimated embodied carbon by material type for each component of the scheme

Category	Material Type	Embodied Carbon (tCO_2)						
		Road Network	Structures	Substructure	Main Crossing			
					Option 1	Option 2	Option 3	Option 4
Cement	Cement: general - 50% blast furnace slag			7,813				
Metals	Steel: general (UK typical)			25,791	70,664	51,220	62,914	43,471
	Steel: general (primary)				233	236	240	243
	Steel: bar & rod (UK Typical)		13,418		12,076	18,257	14,000	20,181
	Steel: bar & rod (Primary)				161	161	161	161
	Steel: section		12,606					
	Steel: wire				10,530	15,217	12,341	17,027
	Steel: stainless				8,445	8,445	8,445	8,445
	Sheet piling: heavy use			15,160				
Misc	Paint (Average)				323	244	286	207
Quarry Sourced Materials	Quarried aggregate			298				
	Recycled aggregate			34				
	General aggregate	4,233	1,413					
	Asphalt	4,468			481	697	481	697
	Sand			113				
	Stone: general			1,515				
Concrete	General Road and Pavement			4,057	22	175	22	175
	High Strength		20,142	1,667	16,222	26,058	20,159	29,995
	Prefabricated Concrete		189					
	Total	**8,701**	**47,768**	**56,448**	**119,157**	**120,710**	**119,049**	**120,602**

5 Carbon Emissions Associated with Earthworks

5.1 Maximising the Cut and Fill Balance

An earthworks strategy has been developed for the proposed scheme that reviews the earthworks material available on site, potential sources of imported material, the earthworks balance, options available for improving the earthworks balance and the impact that the proposed construction programme will have on the earthworks balance. Attention has been paid to earthworks geometry, such as flat slopes to allow lower grade material to be used in fill or steepened slopes with reinforcement, soil nails or reinforced embankments, in an attempt to reduce cut and fill quantities and to minimise the need to import or export fill to and from the site.

The earthworks strategy has allowed the development of the Stage 3 design and will be further developed to aid the final design within the constraints of the EIA and ES, minimising both the volume of imported material required and the surplus destined for disposal.

The import of fill material has been taken account within the carbon footprint calculations presented in Section 4.2 above, where earthworks fill materials have been referred to as ‘general aggregate’. The emission factor for general aggregate was selected as the most appropriate in view of the nature of the earthworks materials likely to be handled.

Notwithstanding the efficiency gains that will be generated by the cut and fill balance, it is estimated that there will be a certain quantity of material that will be unusable and will therefore need to be disposed of and the implications of this to the carbon footprint is covered in Section 5.2 below.

5.2 Export of Unacceptable Earthwork Material

Table 22 provides estimated quantities of earthwork materials to be exported from site. These quantities are based on Stage 3 Design. In total, it is estimated that 115,000m^3 of material would be removed from site (refer to Chapter 4 of the ES). Note that this does not include potential material exported for land-based structures.

Table 22: Estimated quantities of earthwork materials to be removed from site (Stage 3 Design)

	M9 Junction 1a	Queensferry Junction	Ferrytoll Junction
Estimated Export (m^3)	20,000	55,000	40,000

N.B. These quantities do not include potential export of material for structures

Table 24 provides an estimate of the carbon emissions associated with the removal of this waste material from site. It is estimated that the waste is transported on average 35km from site (refer to Table 23).

The emissions factor for transport is taken from the HA Accounting Tool (HA 2008; HA 2009). The calculations indicate that the removal of waste earthwork materials from site results in the emission of an estimated 2,555 tCO_2.

Table 23: Potential material disposal (landfill) sites and estimated distance

Name	Estimated Distance (km)
Binn Farm Landfill	39.9
Avondale Landfill	21.1
Avondale Hazardous Landfill	21.1
West Carron Landfill	31.0
Lochhead Landfill Site	13.7
Oatslie Sandpit Landfill	31.7
Levenseat Landfill	37.5
Greengairs Landfill	56.6
Greenoakhill Landfill	56.5
Average	**35.0**

Table 24: Carbon emissions associated with the removal of waste earthworks material from site

Category	Material	Mass (tonnes)	Average waste removal distance (km)	Road Transport (tCO_2/t.km)	Carbon (tCO_2)
Waste removal	Inert waste	230,000*	35.0	0.0003174	2,555

* Assumed 2.0 tonnes per m^3

6 Options to Reduce Embodied Energy and Carbon

6.1 Use of Recycled Aggregate

As well as maximising the earthworks cut and fill balance which can make a positive contribution to reducing the carbon footprint of the scheme, there may be further potential for reducing embodied energy and carbon associated with the road network by using recycled aggregate from other local sources, where this is appropriate, instead of quarried aggregate.

Table 25: Comparison of carbon values for recycled and quarried aggregate

Type of Material	Embodied Carbon Value (tCO_2/t)
Recycled Aggregate	0.00369
Quarried Aggregate	0.00800

Table 25 above compares embodied carbon values for recycled and quarried aggregate. These values are taken directly from the Highways Agency Carbon Accounting Tool (HA 2008; HA 2009). Based on these values, it is estimated that the carbon intensity of recycled aggregate is 54% lower compared to quarried material.

Transport is likely to be significant for aggregates and the proximity of material sources and method of transport to site could have a greater overall influence on energy and carbon.

There is likely to be a large volume of material generated on site from rock cuts and from quarrying the existing roads that could be processed and re-used on site for capping, sub-base and a percentage of road-base. An earthworks strategy has been developed for the proposed scheme which reviews the earthworks material available on site, potential sources of imported material, the earthworks balance, and options available for improving the earthworks balance. The earthworks strategy will aid the final design and help to minimise both the volume of imported material required and the surplus destined for disposal.

As reported in Section 4.13.2 of the Sustainability Appraisal and Carbon Management Report, earthworks materials will be sourced locally where appropriate with the aim of reducing haulage distance for imported fill and for exported material.

6.2 Using Recycled Steel

Table 26 shows embodied energy and carbon values associated with steel materials from different sources. Values are given for steel from primary sources, secondary sources, and for the market average.

The embodied energy and carbon of steel from secondary sources is approximately 75% lower than that from primary sources (on a tonne for tonne basis). This shows that there may be significant savings to be made (in terms of a reduction in embodied energy and carbon) by using an increased proportion of recycled steel in the project where this is appropriate, as steel accounts for a major proportion of the overall embodied energy and carbon. However, other sustainability factors should also be considered, such as durability and the life span of products, maintenance requirements, performance, and ability to re-use materials after decommissioning.

Table 26: Comparing embodied energy and carbon values for steel

Material	Embodied Energy (MJ/kg)			Embodied Carbon Kg CO_2/Kg		
	UK Typical	Primary	Secondary	UK Typical	Primary	Secondary
General Steel	24.4	35.3	9.5	1.77	2.75	0.43
Bar and Rod	24.6	36.4	8.8	1.71	2.68	0.42

7 Carbon Emissions Associated with Transport of Materials

7.1 Introduction

This section examines emissions of carbon associated with the transport of materials to site. Emissions from transport will depend on: a) the quantity of material to be transported; b) where the material is sourced from (i.e. distance to site); and c) the predominant mode of transport used.

Table 27 provides carbon emissions values associated with different modes of transport. These values are taken from DEFRA's published GHG conversion factors (DEFRA 2009b) and are expressed in terms of kg CO_2e (carbon equivalent) emitted in order to transport one tonne of material a distance of one kilometre. Please note that all DEFRA guidance uses the unit CO_2e (carbon equivalent), rather than just CO_2 as used in the HA model above (refer to Section 2.2).

Table 27: Carbon emission values associated with transport of materials to site (DEFRA 2009b)

Mode of Transport	Carbon Emissions (kg CO_2e/tonne.km)
Articulated HGV (UK average)	0.0860
Rail Freight	0.0319
Shipping (Large bulk carrier)	0.0071

7.2 Illustrative Sourcing Scenarios

For the purposes of this illustrative exercise the following four sourcing scenarios for steel are considered:

Option 1) All steel sourced a distance of **400 km** from site and transported by **rail** to site

Option 2) All steel sourced a distance of **400 km** (approximate distance Edinburgh to Sheffield) from site and transported by **road** to site

Option 3) All steel sourced from **Rotterdam**, the Netherlands, (approximately 730km[2]) and transported by **sea** to site

Option 4) All steel sourced from **China** (approximately 17,000 km[3]) and transported by **sea** to site

The results are summarised below in Table 28. These calculations are for emissions associated with **transport only**. Emissions associated with embodied carbon (i.e. carbon produced during extraction, processing and manufacture) are not shown in Table 28 (as estimated in Section 4 above, total embodied carbon associated steel is approximately 170,000 tCO_2).

Table 28: Carbon emissions associated with the different sourcing options

Material	Total Mass of Steel Material (tonnes)	Carbon Emissions associated with Transport (tCO_2e)			
		Option 1	Option 2	Option 3	Option 4
Steel	90,000	1,148	3,096	466	10,863

[2] http://www.distances.com/
[3] http://www.portworld.com/

Of the three options, Option 3 would result in the lowest amount of CO_2e being emitted, while Option 4 would result in the highest. Option 4 is over 23 times more carbon polluting than Option 3. Choosing option 3 over option 4 would result in a carbon ‘saving’ of 10,397 tCO_2e.

Please note, material quantities are provisional only at this stage and are based on currently available estimates provided by the Design Team. Material quantities will also vary depending on the type of design selected for the Main Crossing. For this exercise, material quantities were based on the selection of the orthotropic option for the cable-stayed bridge and the composite option for the approach viaduct.

Carbon emissions associated with the transport of steel materials to site are relatively low compared to the embodied carbon content in steel (estimated to be between 1% to 5%). Steel has a high embodied energy and carbon content and accounts for a major proportion of the overall ‘footprint’ of the scheme.

8 The Shadow Price of Carbon

8.1 Introduction

In 2007 DEFRA published revised guidance on how to value greenhouse gas emissions in government appraisals (DEFRA 2007b). This is for use in all policy and project appraisals across government with significant effects on carbon emissions. The guidance adopts the concept of the Shadow Price of Carbon (SPC) as the basis for incorporating carbon emissions in cost-benefit analysis and impact assessments.

The shadow price of carbon (SPC) is used to value the expected increase or decrease in emissions of greenhouse gas emissions resulting from a proposed policy. Put simply, the SPC reflects the damage costs of climate change caused by each additional tonne of greenhouse gas emitted – converted into carbon dioxide equivalent (CO_2e) for ease of comparison. The value of the shadow price of carbon used in this report is based on DEFRA guidance of 2007. It should however be noted that since undertaking this exploratory work a recent update on carbon valuation has been produced by the Department of Energy and Climate Change (DECC) - *Carbon Valuation in UK Policy Appraisal: A Revised Approach Climate Change Economics, Department of Energy and Climate Change July 2009* (DECC 2009). Future work on carbon valuation will reflect the changes introduced in this revised approach.

The SPC is different from the previously used social cost of carbon (SCC) in that it takes more account of uncertainty and is based on a stabilisation trajectory. Including the benefits of lower CO_2e emissions from a policy designed to reduce them (or a policy with a different objective that also reduced CO_2e as a co-benefit) in the policy's appraisal would make the policy relatively more attractive - either in comparison to alternatives with worse CO_2e impacts, or by increasing the scale of the benefits relative to costs. Accounting for such environmental benefits aids 'green' policy-making.

Similarly, valuing the additional CO_2e emitted by a policy would add to its overall costs and make it a relatively less attractive option than one with lower additional CO_2e emissions (or indeed CO_2e savings). It is possible that including the monetised value of a policy that increases CO_2e emissions may even switch the balance of costs and benefits so that the costs outweighed the benefits.

8.2 Methodology

DEFRA has produced guidance on how to value greenhouse gas emissions in government appraisal. This guidance is outlined below in four steps:

Step 1: Quantify the impact of greenhouse gas emissions, giving the figures in tonnes of carbon dioxide equivalent

Set out the exact quantity of carbon dioxide – or CO_2 equivalent – the policy is expected to save/emit each year in a spreadsheet. This should be a net change from an assumed baseline rate of emissions. The assumed baseline are emissions in the absence of the policy.

Step 2: Calculate the correct schedule of the Shadow Price of Carbon to use and set it alongside the quantities of greenhouse gas saved

- The value of the Shadow Price of Carbon (SPC) is dependent upon the year the carbon is abated/emitted.
- In the year 2000, in year 2000 prices the SPC is set to £19 per tonne CO_2e.
- The SPC rises over time for two reasons:
    - to account for observed (and assumed) inflation; and

    - increasing by 2 per cent per year to account for rising damage costs from higher greenhouse gas concentrations.

- Do not use the same value of the SPC for each year. Use the tables below to find the SPC for each year of your policy, i.e. a SPC schedule. Alternatively, use the tables to find the SPC in the start year of the policy, then add 2% per year to it.

Table 29: SPC from 2007 to 2050 (in 2009 prices) (adapted from DEFRA 2007b)

Year				2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
SPC in 2009 prices and with 2% pa increases (£)				26.5	27.1	27.6	28.2	28.7	29.3	29.9	30.5	31.1	31.7	32.3	33.0
2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
33.6	34.3	35.0	35.7	36.4	37.1	37.9	38.6	39.4	40.2	41.0	41.8	42.7	43.5	44.4	45.3
2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
46.2	47.1	48.1	49.0	50.0	51.0	52.0	53.1	54.1	55.2	56.3	57.4	58.6	59.8	60.9	62.2

- All values of the SPC listed in Table 29 are in 2009 prices. These values have been adjusted from DEFRA's guidance on greenhouse gas pricing (DEFRA 2007b). For policies appraised in other years or using another year's price level (which may be appropriate if other costs and benefits are in a different year's price level), the SPC must be adjusted.

Step 3: Multiply each year's quantity of greenhouse gas emissions abated/emitted (expressed in CO_2e) by that year's Shadow Price of Carbon

- The spreadsheet should already have each year of the policy's greenhouse gas emissions (expressed in CO_2e), and a SPC schedule. Multiply these year by year.

Step 4: Use the monetised greenhouse gas values in your cost-benefit analysis

- Continue appraising the policy according to Green Book guidance. This includes showing the Net Present Value (NPV) of the carbon impacts in isolation and as part of the overall NPV. It also includes performing sensitivity analysis around the carbon impacts in the same way undertaken for other costs and benefits.
- During sensitivity analysis look out for whether a ±5% change in the SPC would turn a NPV positive policy into NPV negative, or visa versa, or where a higher or lower SPC would change the ranking of different policy options. If this is the case, it should be made clear in the appraisal, and borne in mind in the recommendation.
- Make all assumptions clear in the analysis and Impact Assessment. The policy appraisal must at least state the quantity of greenhouse gases and the value of these (i.e. quantity multiplied by the SPC).

General guidance on greenhouse gas policy appraisal can be found on the DEFRA website. This includes papers on the SPC, which give more detail on the rationale for using SPC and the theoretical background.

8.3 Illustrative Example

The following exercise provides an illustrative example of how the shadow price of carbon could be accounted for during project appraisal. Two scenarios are presented:

- 'Scenario 1' where the option for the main crossing includes an orthotropic steel deck and steel is sourced from Rotterdam (730 km) and transported to site by sea; and
- 'Scenario 2' where the option for the main crossing includes a composite deck and steel is sourced from China (17,000 km) and transported to site by sea.

Table 30: Comparison of embodied carbon associated with four different options for the Main Crossing and approach viaduct

		Cable-Stayed Bridge	
		Orthotropic	Composite
		Embodied Carbon (tCO_2)	
Approach Viaduct	Composite	119,157	120,710
	Concrete	119,049	120,602

Table 31: Comparison between the 'Best Case' and 'Worst Case' scenarios for carbon emissions

	Scenario 1 (tCO_2)	Scenario 2 (tCO_2)
Embodied Carbon	119,049	120,710
Transport of Steel	466	10,863
Total	**119,515**	**131,573**

Based on the above analysis, opting for Scenario 1 over Scenario 2 would result in a carbon 'saving' of:

- 131,573 – 119,515 = 12,058 tCO_2e

8.4 Monetising Carbon

Best practice guidance adopts the concept of the Shadow Price of Carbon (SPC) as the basis for incorporating carbon emissions in cost-benefit analysis and impact assessments. The SPC reflects the damage costs of climate change caused by each additional tonne of greenhouse gas emitted – converted into carbon dioxide equivalent (CO_2e) for ease of comparison. This allows efficiency in design leading to a reduction in embodied carbon to be monetised at a current value.

9 Conclusions

9.1 Background and Purpose

The Forth Replacement Crossing Sustainable Development Policy (refer to Appendix 1) sets out the key sustainability principles and objectives which form a core thread throughout all the activities of the project team and stages in the project life cycle. Reducing the environmental impacts of the scheme, including lowering the carbon footprint, is integral to this policy.

9.2 Approach

This energy and carbon assessment is based on information contained in the Highways Agency Carbon Accounting Tool (HA 2008; HA 2009). Other key sources of data include the Inventory of Carbon and Energy produced by the University of Bath (University of Bath 2008) and DEFRA's GHG conversion factors (DEFRA 2008). Estimated quantities of construction materials to be used in the scheme were provided by the relevant project design teams. The impact of scheme in terms of carbon emissions associated with vehicles using the crossing is discussed within the Chapter 15 (Air Quality) of the ES.

9.3 Results of Embodied Energy and Carbon Assessment

During the early stages of the project design an initial high-level carbon footprinting exercise was carried out to provide a high-level comparison of the carbon emissions associated with two scheme alternatives for the proposed Forth Replacement Crossing.

Based on this early analysis, it was calculated that Option FS2 (involving extensive new road network, three-corridor main crossing with separate provision for public transport) would result in approximately 68% (102,000 tonnes) more embodied carbon than Option MG2 (less extensive road network, two-corridor main crossing, and refurbishment of the FRB to allow use by public transport). This assessment also indicated that steel and concrete were responsible for the majority of the embodied carbon associated with materials to be used in the scheme.

Building on the high-level carbon footprinting exercise carried out at the initial design stage, a more detailed analysis was carried out based on Stage 3 Design which assessed the embodied energy and carbon associated with key materials.

The findings from this assessment indicate that, in the case where Option 1 (orthotropic cable-stayed bridge and composite approach viaduct) is chosen for the Main Crossing superstructure, the total embodied energy for the scheme would be 3,129,574 GJ and the total embodied carbon would be 232,074 tCO_2.

The Main Crossing superstructure (cable-stayed bridge and approach viaduct) makes up the greatest proportion of total embodied energy and carbon. In the case where Option 1 is chosen, the Main Crossing superstructure would account for approximately 48% of the overall embodied energy of the scheme. Under this scenario, the Main Crossing substructure would account for around 24% of total embodied energy, while land-based structures and the road network would make up 17% and 11% respectively.

In terms of which materials make the greatest contributions to overall embodied energy, steel accounts for approximately 75%, quarry source materials (aggregates, stone, asphalt, etc) make up around 14%, while cement and concrete account for around 11% and paint accounts for less than 1% of the total.

9.4 Potential Options to Reduce Energy and Carbon

A number of options are being considered which are aimed at reducing embodied energy and carbon. Some of these include:

- using recycled aggregate rather than quarried aggregate;
- use of other recycled materials such as kerbs, plastic pipes, etc;
- using an increased proportion of recycled steel;
- implementation of a sustainable resource management framework;
- optimisation of cut and fill balance to minimise the need to import, or export, fill from site;
- use of pre-cast technologies; and
- various other design measures to achieve an efficient and economical design, thereby minimising material use.

An initial investigation of the carbon emissions associated with the transport of materials to site was also undertaken as part of this assessment. Various illustrative sourcing scenarios for steel materials were assessed, including: sourcing from within the UK and transporting by rail or road; shipping from Rotterdam to Rosyth; or shipping from China. The results of this exercise indicate that sourcing materials close to site and transporting them by the most sustainable means available could achieve significant carbon savings.

9.5 Operational Carbon

In terms of emissions of greenhouse gases such as CO_2 associated with the operation of the scheme, the ES assessment (Chapter 15: Air Quality) predicted a 14,952 tonne increase in CO_2 emissions in 2017 with the proposed scheme due to more vehicle kilometres being travelled. The scheme will increase the length of the majority of cross-Forth journeys by about 1km because the new crossing is slightly further west than the Forth Road Bridge.

Further assessment was carried out to more fully capture the localised effect of “stop-start” motoring conditions on the congested approaches to the Forth Road Bridge and the localised benefits to be derived from relieving these conditions. The assessment involved modelling a local network in the vicinity of the Forth Replacement Crossing using an alternative approach that better takes into account the emissions from such “stop-start” traffic conditions. Initial findings indicate that during the congested morning peak period, increased CO_2 emissions from the additional distance travelled may be mitigated by reduced congestion that the proposed scheme will deliver relative to the situation without the scheme. There is less congestion relief in the evening peak and therefore the mitigating effect referred to above is less evident during this period.

In terms of impacts from vehicles using the crossing, the FRC scheme includes a number of features aimed at reducing CO_2 emissions. Briefly, these include:

- use of Intelligent Transport Systems to improve network efficiency and decrease congestion;
- promoting modal shift, particularly through the provision of a public transport corridor on the FRB; and
- encouraging and facilitating active modes of transport (e.g. cycling) by minimising impacts on paths and cycle routes and improving these where feasible.

9.6 Next Stages

The energy and carbon assessment will form a ‘baseline’ against which future progress can be monitored. The Contractor will be expected to calculate embodied energy and carbon based on its design and this should not exceed, and should preferably improve on the baseline condition.

Annex A Energy and Carbon Values

Category	Material Type	Conversion	Energy (GJ/t)	Carbon (tCO_2/t)	Comments
Cements	General	1.5 tonnes/m^3	4.6	0.83	
	Cement: general - 25% blast furnace slag	1.86 tonnes/m^3	3.81	0.64	
	Cement: general - 50% blast furnace slag	1.86 tonnes/m^3	3.01	0.45	

Category	Material Type	Conversion	Energy (GJ/t)			Carbon (tCO_2/t)			Comments
			UK Typical	Primary	Secondary	UK Typical	Primary	Secondary	
Metals	Steel: general	8.0 tonnes/m^3	24.4	35.3	9.5	1.77	2.75	0.43	Estimated from UK's consumption of types of steel, and worldwide recycled content 42.7%
	Steel: bar & rod	7.9 tonnes/m^3	24.6	36.4	8.8	1.71	2.68	0.42	
	Steel: section	8.0 tonnes/m^3	25.4	36.8	10	1.78	2.78	0.44	
	Steel: wire	8.0 tonnes/m^3	-	36.00	-	2.83	-	-	
	Steel: stainless	8.0 tonnes/m^3	56.7	-	-	6.15	-	-	
	Sheet piling: heavy use	0.9 tonnes/m^2	24.4	35.3	9.5	1.77			

Category	Material Type	Conversion	Energy (GJ/t)	Carbon (tCO_2/t)	Comments
Misc	Paint (Average)	1.2 kg/litre	68	3.56	Large variations in data, especially for carbon emissions

Category	Material Type	Conversion	Energy (GJ/t)	Carbon (tCO_2/t)	Comments
Quarry Sourced Materials	Quarried aggregate	2.0 tonnes/m^3	0.10	0.008	
	Recycled aggregate	2.0 tonnes/m^3	0.10	0.00369	
	General aggregate	2.0 tonnes/m3	0.10	0.005	ICE database
	General Asphalt	1.7 tonnes/m^3	2.60	0.045	
	Sand	1.85 tonnes/m^3	0.10	0.005	
	Soil	1.7 tonnes/m^3	0.45	0.023	
	Stone: general	2.0 tonnes/m^3	1.00	0.056	Wide data range

Appendix 6: Energy and Carbon Report

Category	Material Type	Conversion	Energy GJ/t	Carbon tCO_2/t	Comments
Concrete	General Road and Pavement	-	1.24	0.127	
	High Strength	-	1.39	0.209	
	Prefabricated Concrete	-	2.00	0.215	
Notes:					
Above values entered from Highways Agency Model and ICE Database on 17/7/09 The HA Model and ICE Database contain a comprehensive range of embodied energy and carbon values for construction materials					

Annex B Embodied Energy and Carbon Calculations

Road and Earthworks

Energy and Carbon Calculations for the Road Network and Earthworks

Component	Category	Material specification	Mass (tonnes)	Energy & Carbon values		Energy	Carbon
				GJ/t	tCO_2/t	GJ	tCO_2
Pavement	Quarry Sourced Material	General Asphalt	88,751	2.60	0.045	230,752	3,994
Overlay		General Asphalt	10,531	2.60	0.045	27,381	474
Sub-base		General aggregate	52,206	0.100	0.005	5,221	261
Capping		General aggregate	104,413	0.10	0.005	10,441	522
Import of fill		General aggregate	690,000	0.10	0.01	69,000	3,450
					Total	**342,794**	**8,701**

Land-Based Structures

Summary of Energy and Carbon Calculations for Land-Based Structures

Structure		Mass (tonnes)	Energy & Carbon values		Energy	Carbon
Category	Material		GJ/t	tCO_2/t	GJ	tCO_2
Concrete	Concrete: high strength	96,372	1.39	0.209	133,957	20,142
	Precast concrete	877	2.00	0.215	1,754	189

Structure		Mass (tonnes)	Estimated Recycled Proportion (%)	Embodied Energy (GJ/t)		Embodied Carbon (tCO_2/t)		Energy	Carbon
Category	Material			UK Typical	Secondary	UK Typical	Secondary	GJ	tCO_2
Metals	Steel: bar & rod	7,847	0	24.6	8.8	1.71	0.42	193,036	13,418
	Steel: section	7,082	0	25.4	10	1.78	0.44	179,883	12,606

Structure		Mass (tonnes)	Energy & Carbon values		Energy	Carbon
Category	Material		GJ/t	tCO_2/t	GJ	tCO_2
Quarry Sourced Materials	General aggregate: Imported Fill	282600	0.100	0.005	28,260	1,413
				Total	**536,890**	**47,768**

Embodied Energy Calculations for Land-Based Structures

Structure		Ferrytoll							Queensferry Junction						
		FT01/02	FT03	FT05	FT07E	FT10E	FT11	FT12	ESQ02	ESQ03	ESQ04	ESQ05	ESQ06	ESQ07	ESQ09E
Category	Material	Embodied Energy GJ													
Concrete	Concrete: high strength	66,484	4,537	3,319	10,258	177	6,946	6,345	3,536	2,819	3,586	4,837	2,102	7,256	40
	Precast concrete	0	0	476	0	0	0	0	0	0	0	0	0	0	252
Metals	Steel: bar & rod	98,154	6,691	5,338	4,772	221	12,398	11,341	4,994	3,764	5,166	7,134	3,100	10,701	320
	Steel: section	147,244	6,985	0	0	0	0	0	6,858	3,556	7,620	0	0	0	0
Quarry Sourced Materials	General aggregate: Imported Fill	12,963	1,220	790	106	0	3,578	2,725	480	411	244	1,292	592	1,574	0

Appendix 6: Energy and Carbon Report

Structure		M9 Junction 1A						TOTAL
		M901	M903	M904	M905E	M907E	M908E	
Category	Material	Embodied Energy GJ						
Concrete	Concrete: high strength	3,210	967	2,572	293	303	4,370	**133,957**
	Precast concrete	0	200	0	0	0	826	**1,754**
Metals	Steel: bar & rod	5,043	1,525	4,723	394	467	6,790	**193,036**
	Steel: section	7,620	0	0	0	0	0	**179,883**
Quarry Sourced Materials	General aggregate: Imported Fill	334	540	486	144	42	738	**28,260**
						Total (GJ)		**536,890**

Appendix 6: Energy and Carbon Report

Information on Land-Based Structures

Structure		Comments
Ferrytoll	FT01/FT02	Mainline Viaduct
	FT03	Ferrytoll Junction North - New Underbridge
	FT05	Railway bridge
	FT06E	Structure Demolished
	FT07E	Widening of Structure
	FT08E	No Works required under Stage 3
	FT09E	No Works required under Stage 3
	FT10E	Minor works
	FT11	Proposed Retaining Wall
	FT12	Retaining Wall Gyratory Interchange South Bound
Queensferry Junction	ESQ02	Queensferry Junction North
	ESQ03	Queensferry Junction South
	ESQ04	New Overbridge
	ESQ05	Pipe Protection System
	ESQ06	Pipe Protection System
	ESQ07	Pipe Protection System
	ESQ08E	Structure Demolished
	ESQ09E	Minor Parapet Works
M9 Junction	M901	New Overbridge
	M903	New Underbridge
	M904	New Swine Burn Culvert
	M905E	Minor works
	M906E	Structure Retained
	M907E	Culvert Extension
	M908E	Reconstruction of Western Section

Information on Main Crossing Substrutures:

SNTBP	South and north tower bases		ASLPr	Approach span piers, S3 to S8 and N3
STP	South tower piles		ASMPr	Approach span piers, S1, S2, N1 and N2
NTP	North tower piles		ACS (Piled)	S1 to S4, N1 pile caps and piles
CTB	Central tower base		ACS (Pad)	S5 to S8 and N2, pads

Appendix 6: Energy and Carbon Report

Embodied Carbon Calculations for Land-Based Structures

Structure		Ferrytoll							Queensferry Junction						
		FT01/02	FT03	FT05	FT07E	FT10E	FT11	FT12	ESQ02	ESQ03	ESQ04	ESQ05	ESQ06	ESQ07	ESQ09E
Category	Material	Embodied Carbon (tCO_2)													
Concrete	Concrete: high strength	9,996	682	499	1,542	27	1,044	954	532	424	539	727	316	1,091	6
	Precast concrete	0	0	51	0	0	0	0	0	0	0	0	0	0	27
Metals	Steel: bar & rod	6,823	465	371	332	15	862	788	347	262	359	496	215	744	22
	Steel: section	10,319	490	0	0	0	0	0	481	249	534	0	0	0	0
Quarry Sourced Materials	General aggregate: Imported Fill	648	61	40	5	0	179	136	24	21	12	65	30	79	0

Structure		M9 Junction 1A						TOTAL
		M901	M903	M904	M905E	M907E	M908E	
Category	Material	Embodied Carbon (tCO_2)						
Concrete	Concrete: high strength	483	145	387	44	46	657	**20,142**
	Precast concrete	0	22	0	0	0	89	**189**
Metals	Steel: bar & rod	351	106	328	27	32	472	**13,418**
	Steel: section	534	0	0	0	0	0	**12,606**
Quarry Sourced Materials	General aggregate: Imported Fill	17	27	24	7	2	37	**1,413**
						Total (tCO_2)		**47,768**

Summary of Embodied Energy and Carbon Associated with Land-Based Structures

Structure	Embodied Energy GJ	Percentage of Total	Embodied Carbon tCO_2	Percentage of Total
FT01/FT02	324,845	61%	27,786	58%
FT03	19,433	4%	1,698	4%
FT05	9,924	2%	961	2%
FT07E	15,137	3%	1,879	4%
FT10E	398	0%	42	0%
FT11	22,922	4%	2,085	4%
FT12	20,411	4%	1,879	4%
ESQ02	15,868	3%	1,383	3%
ESQ03	10,550	2%	955	2%
ESQ04	16,616	3%	1,445	3%
ESQ05	13,263	2%	1,288	3%
ESQ06	5,793	1%	561	1%
ESQ07	19,531	4%	1,914	4%
ESQ09E	612	0%	55	0%
M901	16,207	3%	1,384	3%
M903	3,233	1%	300	1%
M904	7,781	1%	739	2%
M905E	831	0%	79	0%
M907E	812	0%	80	0%
M908E	12,724	2%	1,255	3%
Total	**536,890**	**100%**	**47,768**	**100%**

Main Crossing Substructure

Energy and Carbon Calculations for the Main Crossing Substructure

Structure		Mass (tonnes)	Energy & Carbon values		Energy	Carbon
Category	Material		GJ/t	tCO_2/t	GJ	tCO_2
Cements	Cement: general - 50% blast furnace slag	17,362	3.01	0.45	52,260	7,813

Structure		Mass (tonnes)	Estimated Recycled Proportion (%)	Embodied Energy (GJ/t)		Embodied Carbon (tCO_2/t)		Energy	Carbon
Category	Material			UK Typical	Secondary	UK Typical	Secondary	GJ	tCO_2
Metals	Steel: general	23,446	50	24.4	9.5	1.77	0.43	397,410	25,791
	Sheet piling: heavy use	8,565	0	24.4		1.77	0	208,986	15,160

Structure		Mass (tonnes)	Estimated Recycled Proportion (%)	Embodied Energy (GJ/t)		Embodied Carbon (tCO_2/t)		Energy	Carbon
Category	Material			UK Typical	Secondary	UK Typical	Secondary	GJ	tCO_2
Quarry Sourced Materials	Quarried aggregate	37,259	-	0.1		0.008		3,726	298
	Recycled aggregate	5,822	50	-	0.1	-	0.00369	582	34
	Sand	22,643	-	0.1		0.005		2,264	113
	Stone: general	27,060	-	1.0		0.056		27,060	1,515

Structure		Mass (tonnes)	Energy & Carbon values		Energy	Carbon
Category	Material		GJ/t	tCO_2/t	GJ	tCO_2
Concrete	General Road and Pavement	31,947	1.24	0.127	39,614	4,057
	High Strength	7,974	1.39	0.21	11,084	1,667

Total	**742,986**	**56,448**

Embodied Energy Calculations for the Main Crossing Substructure

Structure		Estimated Recycled Proportion (%)	SNTP	STP	NTP	CTB	ASC (Piled)	ASC (Pad)	ASMPr	ASLPr	Total
Category	Material		Embodied Energy (GJ)								
Cements	Cement: general - 50% blast furnace slag	-	26,334	0	0	5,860	9,081	3,763	2,989	4,232	52,260
Metals	Steel: general	50	199,298	14,967	12,831	11,577	131,905	8,645	7,661	10,526	397,410
	Sheet piling: heavy use	-	91,256	42,432	32,989	0	42,310	0	0	0	208,986
Quarry Sourced Materials	Quarried aggregate	-	1,675	0	0	0	948	378	300	425	3,726
	Recycled aggregate	50	462	0	0	120	0	0	0	0	582
	Sand	-	994	0	0	0	535	252	200	283	2,264
	Stone: general	-	0	0	0	0	23,540	3,520	0	0	27,060
Concrete	General Road and Pavement	-	0	18,676	15,995	4,944	0	0	0	0	39,614
	High Strength	-	0	0	0	11,084	0	0	0	0	11,084

Total (GJ) **742,986**

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Appendix 6: Energy and Carbon Report

Embodied Carbon Calculations Substructure

Structure		Estimated Recycled Proportion (%)	SNTP	STP	NTP	CTB	ASC (Piled)	ASC (Pad)	ASMPr	ASLPr	Total
Category	Material		Embodied Carbon (tCO_2)								
Cements	Cement: general - 50% blast furnace slag	-	3,937	0	0	876	1,358	563	447	633	7,813
Metals	Steel: general	50	12,934	971	833	751	8,560	561	497	683	25,791
	Sheet piling: heavy use	-	6,620	3,078	2,393	0	3,069	0	0	0	15,160
Quarry Sourced Materials	Quarried aggregate	-	134	0	0	0	76	30	24	34	298
	Recycled aggregate	50	27	0	0	7	0	0	0	0	34
	Sand	-	50	0	0	0	27	13	10	14	113
	Stone: general	-	0	0	0	0	1,318	197	0	0	1,515
Concrete	General Road and Pavement	-	0	1,913	1,638	506	0	0	0	0	4,057
	High Strength	-	0	0	0	1,667	0	0	0	0	1,667
									Total (tCO_2)		**56,448**

Main Crossing Superstructure

Energy and Carbon Calculations for Main Crossing Superstructure Options Summary

Cable Stay Bridge - Single Deck Box Girder - Orthotropic						
Category	**Material**	**Mass (tonnes)**	**Energy and Carbon Values**		**Energy**	**Carbon**
			GJ/t	**GJ**	**GJ**	**tCO_2**
Metals	Steel: general (UK typical)	34,412	24.40	1.77	839,641	60,908
	Steel: general (primary)	49	35.30	2.75	1,723	134
	Steel: bar & rod (UK Typical)	4,712	24.60	1.71	115,915	8,058
	Steel: bar & rod (Primary)	60	36.40	2.68	2,184	161
	Steel: wire	3,721	36.00	2.83	133,956	10,530
	Stainless steel	1,156	56.70	6.15	65,545	7,109
Misc	Paint: 100um thickness	48	68	3.56	3,288	172
	Paint: 300um thickness	32	68	3.56	2,177	114
Quarry Sourced Materials	25mm Asphalt	227	2.60	0.045	589	10
	70mm Asphalt	5,011	2.60	0.045	13,030	226
	125mm Asphalt	2,359	2.60	0.045	6,133	106
Concrete	Concrete (high strength)	52,452	1.39	0.209	72,908	10,962
	Concrete (general road and pavement)	0	1.24	0.127	0	0
				Total	**1,257,089**	**98,491**

Cable Stay Bridge - Single Deck Box Girder - Orthotropic				
Material	**Embodied Energy (GJ)**	**Percentage of Total**	**Embodied Carbon (tCO_2)**	**Percentage of Total**
Steel: general (UK typical)	839,641	67%	60,908	62%
Steel: general (primary)	1,723	0%	134	0%
Steel: bar & rod (UK Typical)	115,915		8,058	
Steel: bar & rod (Primary)	2,184	0%	161	0%
Steel: wire	133,956		10,530	
Stainless steel	65,545	5%	7,109	7%
Paint	5,465	0%	286	0%
Asphalt	19,752	2%	342	0%
Concrete (high strength)	72,908	6%	10,962	11%
Concrete (general road and pavement)	0	0%	0	0%
Total	**1,257,089**	**100%**	**98,491**	**100%**

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Appendix 6: Energy and Carbon Report

Cable Stay Bridge - Single Deck Box Girder - Composite

Category	Material	Mass (tonnes)	Energy and Carbon values GJ/t	Energy and Carbon values tCO_2/t	Energy GJ	Carbon tCO_2
Metals	Steel: general (UK typical)	23,427	24.40	1.77	571,607	41,465
	Steel: general (primary)	50	35.30	2.75	1,757	137
	Steel: bar & rod (UK Typical)	8,327	24.60	1.71	204,844	14,239
	Steel: bar & rod (Primary)	60	36.40	2.68	2,184	161
	Steel: wire	5,377	36.00	2.83	193,572	15,217
	Stainless steel	1,156	56.70	6.15	65,545	7,109

Category	Material	Mass (tonnes)	Energy and Carbon values GJ/t	Energy and Carbon values tCO_2/t	Energy GJ	Carbon tCO_2
Misc	Paint: 100um thickness	26	68	3.56	1,776	93
	Paint: 300um thickness	32	68	3.56	2,177	114

Category	Material	Mass (tonnes)	Energy and Carbon values GJ/t	Energy and Carbon values tCO_2/t	Energy GJ	Carbon tCO_2
Quarry Sourced Materials	25mm Asphalt	1,086	2.60	0.045	2,824	49
	70mm Asphalt	0	2.60	0.045	0	0
	125mm Asphalt	11,308	2.60	0.045	29,400	509

Category	Material	Mass (tonnes)	Energy and Carbon values GJ/t	Energy and Carbon values tCO_2/t	Energy GJ	Carbon tCO_2
Concrete	Concrete (high strength)	99,516	1.39	0.209	138,327	20,799
	Concrete (general road and pavement)	1,200	1.24	0.127	1,488	152

Total	**1,215,501**	**100,044**

Appendix 6: Energy and Carbon Report

Cable Stay Bridge - Single Deck Box Girder - Composite				
Material	**Embodied Energy (GJ)**	**Percentage of Total**	**Embodied Carbon (tCO_2)**	**Percentage of Total**
Steel: general (UK typical)	571,607	47%	41,465	41%
Steel: general (primary)	1,757	0%	137	0%
Steel: bar & rod (UK Typical)	204,844	17%	14,239	14%
Steel: bar & rod (Primary)	2,184	0%	161	0%
Steel: wire	193,572	16%	15,217	15%
Stainless steel	65,545	5%	7,109	7%
Paint	3,953	0%	207	0%
Asphalt	32,224	3%	558	1%
Concrete (high strength)	138,327	11%	20,799	21%
Concrete (general road and pavement)	1,488	0%	152	0%
Total	**1,215,501**	**100%**	**100,044**	**100%**

Energy and Carbon Calculations for Approach Bridge Options

Approach Bridge - Twin Composite Box Girder						
Category	**Material**	**Mass (tonnes)**	**Energy and Carbon Values**		**Energy**	**Carbon**
			GJ/t	**GJ**	**GJ**	**tCO_2**
Metals	Steel: general (UK typical)	5,511	24.40	1.77	134,479	9,755
	Steel: general (primary)	36	35.30	2.75	1,271	99
	Steel: bar & rod	2,350	24.60	1.71	57,807	4,018
	Steel: wire	0	36.00	2.83	0	0
	Stainless steel	217	56.70	6.15	12,315	1,336
Misc	Paint: 100um thickness	3	68	3.56	200	10
	Paint: 300um thickness	7	68	3.56	499	26
Quarry Sourced Materials	25mm Asphalt	164	2.60	0.045	426	7
	70mm Asphalt	0	2.60	0.045	0	0
	125mm Asphalt	2,931	2.60	0.045	7,620	132
Concrete	Concrete (high strength)	25,165	1.39	0.209	34,979	5,259
	Concrete (general road and pavement)	176	1.24	0.127	218	22
				Total	**249,815**	**20,666**

Appendix 6: Energy and Carbon Report

Approach Bridge - Twin Composite Box Girder						
Category	Material	Mass (tonnes)	Energy and Carbon Values		Energy	Carbon
			GJ/t	GJ	GJ	tCO_2
Metals	Steel: general (UK typical)	1,133	24.40	1.77	27,650	2,006
	Steel: general (primary)	39	35.30	2.75	1,359	106
	Steel: bar & rod	3,475	24.60	1.71	85,482	5,942
	Steel: wire	640	36.00	2.83	23,030	1,810
	Stainless steel	217	56.70	6.15	12,315	1,336
Misc	Paint: 100um thickness	0	68	3.56	0	0
	Paint: 300um thickness	0	68	3.56	0	0
Quarry Sourced Materials	25mm Asphalt	164	2.60	0.045	426	7
	70mm Asphalt	0	2.60	0.045	0	0
	125mm Asphalt	2,931	2.60	0.045	7,620	132
Concrete	Concrete (high strength)	44,003	1.39	0.209	61,164	9,197
	Concrete (general road and pavement)	176	1.24	0.127	218	22
				Total	**219,265**	**20,558**

Approach Bridge - Twin Concrete Box Girder				
Material	**Embodied Energy (GJ)**	**Percentage of Total**	**Embodied Carbon (tCO_2)**	**Percentage of Total**
Steel: general (UK Typical	27,650	13%	2,006	10%
Steel: general (UK Primary)	1,359	1%	106	1%
Steel: bar & rod	85,482	39%	5,942	29%
Steel: wire	23,030	11%	1,810	9%
Stainless steel	12,315	6%	1,336	6%
Paint	0	0%	0	0%
Asphalt	8,046	4%	139	1%
Concrete (high strength)	61,164	28%	9,197	45%
Concrete (general road and pavement)	218	0%	22	0%
Total	**219,265**	**100%**	**20,558**	**100%**

Combination of Options for Main Crossing

		Cable Stay Bridge	
		Orthotropic	Composite
		Embodied Energy (GJ)	
Approach Viaduct	Composite	1,506,904	1,465,316
	Concrete	1,476,353	1,434,766

		Cable Stay Bridge	
		Orthotropic	Composite
		Embodied Energy (GJ)	
Approach Viaduct	Composite	119,157	120,710
	Concrete	119,049	120,602