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An embodied carbon and embodied energy appraisal of a section of Irish motorway constructed in peatlands

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Abstract

In addition to the customary drivers of cost and timely project delivery, embodied energy (EE) and embodied carbon (EC) have come to prominence in recent years as major design considerations in all aspects of large-scale road construction projects. An assessment of road construction necessitating the excavation or alteration of peat should consider the impact on carbon stored within the peat and the greenhouse gases potentially released. A methodology for calculating the environmental impact of constructing roads on peat is presented in this paper. Furthermore, the paper describes the application of this methodology (focusing on EE and EC calculations) to a case study; a section of the M6 motorway in Ireland for which excavate-and-replace was the ground improvement method (Scenario ER). A range of peat-related factors impacting on EE and EC estimates were examined, including materials, transport and machinery, as well as more unfamiliar factors such as peat drainage, drainage systems, restoration, slope stability and clearance of vegetation/forest. Comparisons of total EC are investigated under various management practices and restoration techniques for peatlands, assessing their strength in terms of hydrology and carbon storage potential. The total EC and EE for road construction to the sub-base level (and implications thereof) of the 2.14 km section of the M6 discussed in this paper was 17220 tCO2eq (8047 tCO2eq/km) and 54541 GJ (25487 GJ/km) respectively, with carbon loss from excavated peat accounting for 62% of the total EC. Two other ground improvement method scenarios for constructing this section of road were also considered: Scenario S, soil-mixing and Scenario ER+P, an appropriate combination of excavate-and-replace and piling. Scenario S gave rise to a total EC of 25306 tCO2eq (11825 tCO2eq/km) and a total EE of 164364 GJ (76806 GJ/km) while Scenario ER+P gave rise to a total EC of 17048 tCO2eq (7966 tCO2eq/km) and a total EE of 92706 GJ (43320 GJ/km). In this study, Scenario ER was the preferred technique as it had EC comparable to Scenario ER+P and the lowest EE. On the other hand, Scenario S was the least favourable due to the high EC and EE of the binder. However, this paper shows that the EC and EE can be decreased dramatically by changing the binder proportions. Furthermore, the EC of Scenarios ER and ER+P can also be significantly reduced if alternative restoration techniques are employed for excavated peat.

1. Introduction and context of research

In the decade 2000-2010, the length of motorway and dual carriageway in the Republic of Ireland approximately quadrupled to a total of 1200 km [1]. Given that peatlands account for 13.8% of Ireland's land area [2], it was inevitable that peat would be encountered in large expanses on some of these projects. For geotechnical engineers, peat represents a challenge because of its high moisture content, low shear strength and high compressibility (especially its propensity for long-term creep settlements). Some form of ground improvement is normally required when it is encountered on road projects. The favoured option for road construction in Ireland to date has been to excavate the peat, particularly where the depth is no greater than 3-4 m [3] and replace it with competent fill material. However, in some road projects in Ireland, depths greater than 4 m were excavated, with local excavations reaching depths of up to 13 m [3]. Piling, on the other hand, because of its high cost, has generally been used only where settlement control was paramount. Some projects have also considered dry soil-mixing, whereby a dry binder (typically some combination of cement and ground granulated blast furnace slag) is injected into the peat to create a stabilised platform, but in most cases it was not deemed commercially viable because of the large amounts of binder required [4]. Surcharging, another option, is not currently permitted for peat soils by the National Roads Authority in Ireland. The use of any of these methods for supporting roads necessitates the generation of a substantial amount of construction materials, leading to the depletion of natural resources, the emission of greenhouse gases and damage to the local environment due to construction operations.

Ireland has an obligation to reduce its annual non Emissions Trading Scheme (non-ETS) greenhouse gases emitted to at least 20% below 2005 levels by 2020 or face significant fines under the legally-binding EU's '20-20-20' Initiative [5]. In 2005, the Irish construction sector was domestically responsible for the emission of 8.11 MtCO_2eq [6], amounting to 11.7% of the country's emissions of 69.3 MtCO_2eq [5], where CO_2 equivalents (CO_2eq) include not only CO_2 but also other greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O) and perfluorocarbons (PFCs), taking account of their global warming potential as set out in the Kyoto protocol. Global warming potential is based on the relative amounts of heat trapped in the atmosphere by greenhouse gas; for example, CO_2 and CH_4 have global warming potentials of 1 and 25 respectively [7]. It is anticipated that Ireland will violate its non-ETS annual greenhouse gas emissions commitments from 2016 onwards, exceeding its EU 2020 target by between 4.1 (11%) and 7.8 MtCO_2eq (21%) [5]. To combat these soaring emissions and comply with regulations, it is vital to be in a position to produce accurate calculations of construction-related energy consumption and emissions, including the geotechnical elements of projects. This will enable engineers to appraise various options with a view to minimising environmental impacts.

Recently, the geotechnical profession has taken steps to quantify energy consumption and emissions for construction projects. Egan and Slocombe [8] investigated the Embodied Carbon (EC) of several piling options on a range of construction projects, while Chau *et al.* [9] examined the Embodied Energy (EE) associated with the construction of sections of a

UK rail tunnel. Both Milachowski *et al.* [10] and Chappat and Bilal [11] estimated the environmental impact of constructing roads. However, despite the increasing demands for sustainable engineering practices, there is a dearth of Life Cycle Assessment (LCA) studies, methodologies and figures for geotechnical projects. This probably accounts for the absence of guidelines on how to determine the potential construction-related emissions (at planning and design stages) associated with road construction in areas of organic soil such as peat.

In this paper, a LCA methodology is outlined which allows a quantitative comparison of the potential environmental impacts of various ground improvement options for road construction on peat, including excavate-and-replace (ER), dry soil-mixing (S) and piling (P). The methodology was applied to a study section of a recent Irish motorway project for which the excavation and replacement of peaty soil was the chosen solution (Scenario ER). Results for total EE and EC for this case study are calculated. Alternative ground improvement scenarios that could have been considered on the same site were also examined, i.e. soil mixing (Scenario S) and a combination of excavate-and-replace and piling (Scenario ER+P). Only aspects of the road construction to the sub-base level and related implications were included in the calculations. Pavement layers were common to all ground improvement scenarios considered and were therefore excluded in the interests of clarity.

2. EC/EE considerations in peatlands

2.1 Construction in peatlands

Peat is a soft organic soil formed in high water table environments where the supply of organic material to the surface surpasses the rate of decomposition due to anaerobic conditions [12]. Consequently, peat accumulates over time, slowly taking in carbon from the atmosphere in the process. In Ireland's three main bog types (raised bogs, blanket bogs, and fens), undisturbed peatlands have been sequestering carbon for thousands of years, exerting a net cooling effect on the world's atmosphere. Many of these peatlands are now disturbed and are net sources of CO_2.

Using existing EE and EC methods, it might be expected that the excavate-and-replace option would be less energy/carbon intensive than soil-mixing and piling, as replacement of peat with fill such as quarried material is relatively cheap and environmentally friendly. The EE associated with producing the binder in soil-mixing and the cement for the concrete in piles is energy intensive because of the additional manufacturing stage and, in general, high EE activities engender high EC. However, the excavation process and the extent of drainage due to construction have a negative impact as a drained peatland releases its stored carbon as CO_2 and other greenhouse gases and thereafter loses its ability to sequester carbon [13].

The higher the organic content of a soil, the higher the potential for loss of carbon as CO_2. In the absence of organic content values, the Scottish Natural Heritage [14] proposed that the carbon content of peat may be estimated at between 49% to 62% of its dry weight. Using this method, the carbon content of peat having a typical dry density of 0.1 g/cm^3 would lie between 0.18 and 0.23 tCO$_2$eq/m^3. However, it is preferable to quantify the organic content of the peat by the loss-on-ignition method [15]. Schumacher [16] suggests finding carbon content by dividing the organic content values by a factor, which has been derived by experiment and ranges between 1.724 (representing 58% carbon) and 2.5 (representing 40% carbon). In general, the range of organic contents found in peat soils is greater than the range of carbon contents found in the organic matter, thereby justifying the latter approach [16].

2.2 Life cycle assessment (LCA)

Environmental LCA tools involve quantifying and evaluating the environmental burden associated with a product or process by considering energy and material uses and releases into the environment. LCA tools can be utilised to implement opportunities to decrease the environmental cost of road construction. A LCA includes four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment, and (iv) interpretation [17]. Having defined the LCA goal, the following are identified in Phase 1: functional unit (e.g. tCO_2eq/m^3, tCO_2eq/t, tCO_2eq/km), system boundary (factors involved), data requirements, and limitations. Phase 2 involves the collection of information on EE/EC intensities from existing databases and other published material to create a database for materials and processes that lie within the system boundary. Phase 3 focuses on performing the assessment, while in Phase 4 the results are interpreted in order to make recommendations and arrive at conclusions.

In an environmental LCA, it is usual to examine global warming (e.g. EC and EE), although other category indicators such as (but not limited to) impacts from water and land use, acidification, eutrophication and ecotoxicity can be used [18, 19, 20]. Where possible, EC is taken as the greenhouse emissions released and is measured in CO_2 equivalents (CO_2eq), found by multiplying the mass of the greenhouse gases by their associated 100-year global warming potential [7]. EE is associated with the energy consumed over a product's life cycle [21]. .

2.3 Use of emission and peat-related factors in LCA studies

In order to understand and quantify the dynamics of gas emissions from peatlands, the Intergovernmental Panel on Climate Change (IPCC) has published basic Tier 1 default emission factors for peatlands in different climates [22]. With the help of these emission factors and other basic assumptions, both Hall [23] and Nayak *et al.* [24] were able to estimate the carbon cost of building a windfarm on peat and investigate the effect of forest removal and drainage. Notwithstanding this progress to date, only a limited number of peat-related factors have been incorporated into EE/EC studies using simple calculations. This paper employs several methodologies to estimate the EC and EE associated with road construction on peatlands and uses Tier 2 country-specific emission factors in addition to established Tier 1 emission factors [22]. The estimation of EC for a particular method of road construction depends on a wide range of factors and construction activities such as construction operations, peat drainage, peat stability, restoration of peatlands, vegetation/forest, and the effect of climate change [25].

2.4 Forest and peatland carbon sinks

In order to help offset the degradation of land and the environmental cost of a construction project, it is possible to include forest and peatland carbon sinks in the EE/EC assessment. To this end, afforestation and peatland restoration can be carried out in conjunction with a road construction project, thereby accumulating carbon credits which have a market value. Under the Land Use, Land Use Change and Forestry (LULUCF) category and the Kyoto Protocol, forest and peatland carbon sinks will, more than likely, be included in Ireland's emissions in 2020. Forest sinks could play a vital role in reducing Ireland's emissions and are predicted to remove 4.6 $MtCO_2eq$ by 2020 [5]. However, as recognised by LULUCF negotiators, drained peatlands and the restoration of wetlands and previously drained peatlands can act as both carbon sinks and significant contributors of greenhouse gas emissions [26] and have the potential to offset annual emissions if accounted for in the post-Kyoto Protocol commitment period from 2013. Greenhouse gas emissions and removals related to LULUCF are not currently included in the EU 2020 target but, nevertheless, must be recorded [5].

3. Case study: M6, Pollboy section

3.1 Introduction

The M6 Galway to East Ballinasloe motorway scheme in the West of Ireland was the final stage of an overall route, approximately 190 km long, connecting Dublin to Galway. The scheme comprised 56 km of motorway, a 7 km link road to Loughrea and 32 km of side and link roads [27]. The mainline is a four-lane dual carriageway with a pavement width of 22 m, and verges of 2 m in accordance with National Roads Authority guidelines in Ireland [28]. Peat underlay approximately 4% of the route. The study section considered in this paper is 2.14 km long, in an area of predominantly peaty soil at Pollboy, south of Ballinasloe (approximately 53°18'59''N, 8°13'55''W to 53°18'49''N, 8°12'01''W; Chainage (Ch.) 52210-54350, see Figure 1). Peat excavate-and-replace (henceforth referred to as Scenario ER) was chosen as the ground improvement technique.

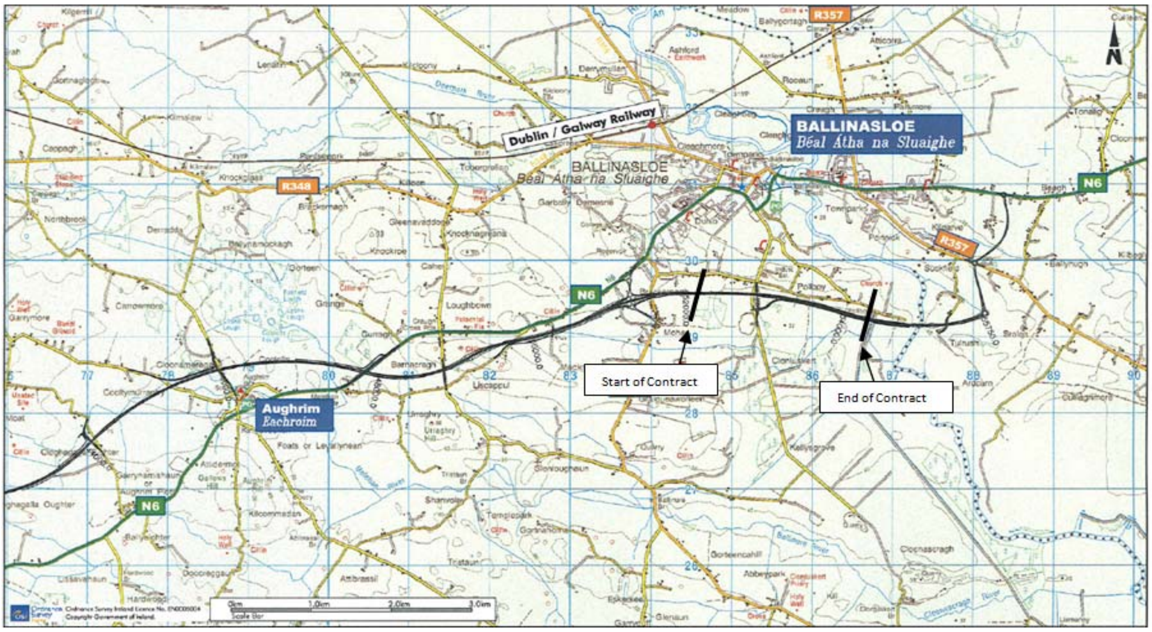


Figure 1 – Location of the M6 motorway and the Pollboy Contract, adapted from RPS [27]

3.2 Geology

The road section lies in the River Suck catchment, with the River Suck about 2 km to the east. The mean annual rainfall is approximately 1150 mm; the mean annual evaporation loss is 460 mm; and the average annual temperature is 9.8 °C [27]. The site has a slope of around 0.5° from north to south and is located in wet land including a mixture of drained reclaimed and unreclaimed fields with an underlying layer of peat and peaty clay, hereafter referred to collectively as peat. This site also borders the Pollboy cutover bog (Ch. 52930-53530). The peatlands had previously been drained, leaving the water table level below the peat layer (Figure 2). Between the start of the section and the River Suck, a significant thickness of alluvial material overlain by peat deposits prevails. In general, good ground conditions exist north of the road alignment and poorer conditions to the south. Peat in the area was found to have moisture contents ranging between 500-1000%, organic contents from 25-80%, oedometer coefficients of volume compressibility (m_v) values of approximately 2-4 m^2/MN, and oedometer coefficient of consolidation (c_v) values of 0.9-1.5 m^2/yr.

3.3 Road construction and ancillary details

An estimated 115000 m^3 of peat was excavated for the motorway mainline and replaced with 170000 m^3 of engineered fill material from nearby quarries (the extra 55000 m^3 was employed to establish a higher foundation level for the sub-base). The excavated volumes necessitated three peat disposal areas along with drainage works comprising of ponds and infiltration ditches. These additional excavations, as well as a stream diversion, accounted for an additional 20173 m^3 of excavated peat. Two wet fields and an open area of moorgrass-covered bog south of the alignment were chosen to site the embankments, which have side slopes of 1:4 and a maximum height of 2 m. A plan identifying these elements of the scheme is shown in Figure 2. A birch/willow woodland was subsequently planted on the peat disposal areas to blend in with the surrounding landscape.

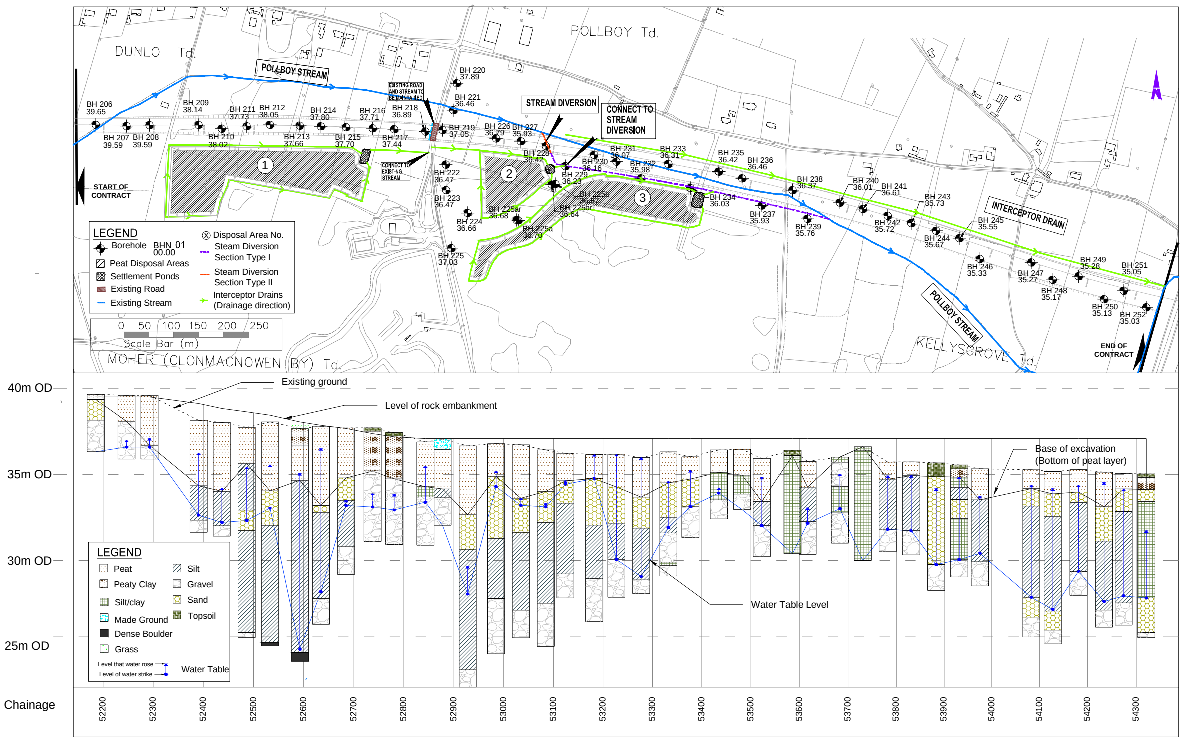
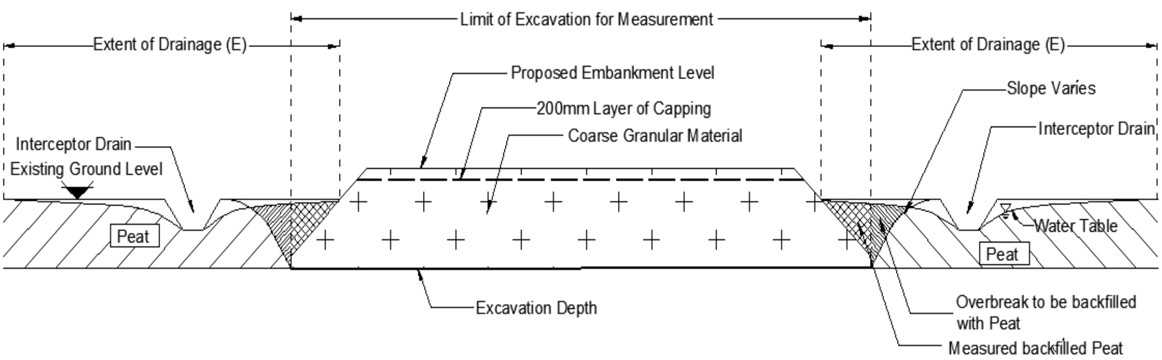


Figure 2 – Plan and cross section of contract

The road embankment has a maximum height of 4.2 m and incorporates a geogrid for extra strength (Figure 3(a)). Deep deposits of soft silt/clay underlay the peat layer in three zones, which were located at the following chainages: Ch. 52400-52700, Ch. 53000-Ch. 53350, and Ch. 53770-54430 (Figure 2). Since the soft silt/clay has c_v values ranging from 2-5 m^2/yr, prefabricated vertical drains (band drains) were required to accelerate drainage under embankment loading. A drainage blanket of 1.5 m in height was employed to lay the band drains in these three parts of the section (Figure 3(b)).



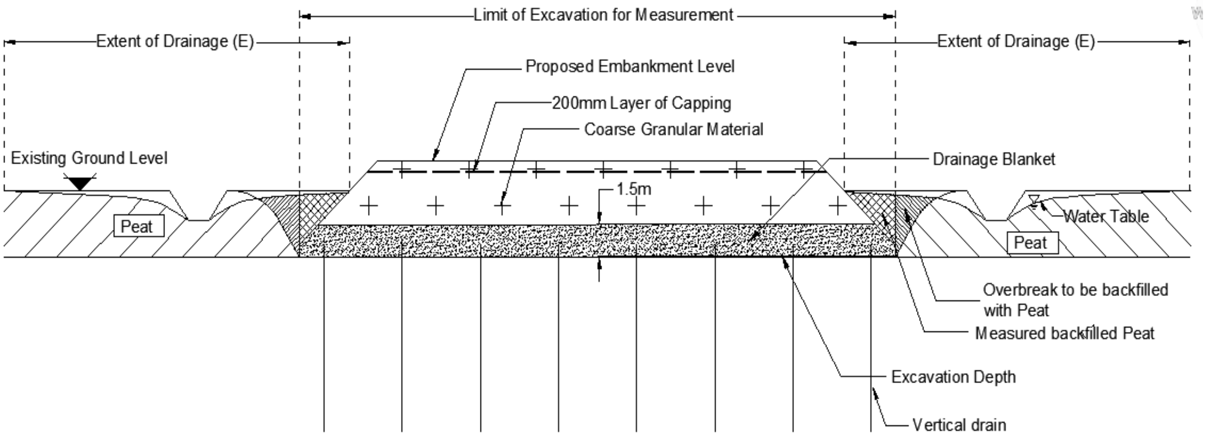


Figure 3 – Typical cross sections of (a) rock embankment (top) (b) rock embankment with vertical drains (bottom) (Courtesy of RPS Group)

The drainage system consists of retention ponds, infiltration ditches and two types of stream diversion. The retention ponds are 0.5 m deep, with a 1:4 side slope and are lined with a permeable geotextile and a 150 mm depth of rockfill. The infiltration ditches around the peat disposal areas have a base width of 1 m, are 1 m in depth and have a 1:1 side slope. As the road alignment crossed a stream, two types of stream diversion had to be built, requiring the excavation of peat to a depth of 2 m in the first type and to 2.5 m in the second. Both types have side slopes of 1:2, with the second case requiring the laying of an impermeable geomembrane and a 150 mm depth of rockfill lining.

4 Carbon and energy calculation

4.1 Goal and scope definition

The goal of the study is to present a methodology that geotechnical engineers can deploy on projects to determine the environmental impact of road construction in areas of highly organic soils, where EE and EC are used as indicators. Thus, the construction of a control segment of aforementioned M6 scheme is utilised as a case study to highlight the key considerations in performing environmental LCA for this application. While excavate-and-replace was adopted in the contract, the study has been extended by also considering potential EE/EC associated with alternatives, such as soil-mixing and piling, and other ancillary activities are also considered in Section 5. For the purposes of this study, the entire 2.14 km section was examined, but a functional 1 km unit was also considered. The calculations have been performed using LCA methodology conforming to ISO 14040 [17].

The function of the scheme is to support pavement layers and vehicular traffic, while meeting the engineering specifications set out by the National Roads Authority in Ireland [28]. The functional unit is defined in this study as a kilometre of motorway operational for 120 years. According to the Highways Agency [29], the design lifetime of geotechnical structures such as embankments should range from 60-120 years. Based on the upper limit of this standard, the boundary of the LCA study starts at the extraction of raw materials and ends when the design lifetime of the road foundation expires after 120 years.

This study adopts the process analysis approach utilising a range of published EE and EC intensities, much of which come from the Inventory of Carbon and Energy Version 2.0 (ICE V2.0) [21] and [30]. The system boundaries employed in the study for an excavation and replacement approach (Scenario ER) for road construction on highly organic soil are given in Figure 4, where the dotted line represents the system boundary and the black arrows indicate transport. Recurring EC and EE in the form of maintenance (e.g. resurfacing roads, line painting, new signage etc.) were not taken into account as the pavement layers were excluded. Materials, transport and machinery all have cradle-to-site boundary conditions, while direct and indirect emissions on-site, on the other hand, are taken into account for the full life cycle. Direct emissions originate from the excavated peat, while indirect emissions come from land construction activities such as emissions from ponds, drainage systems, peat disposal areas and roads, some of which may go into direct emissions and some into the restoration category.

Following the establishment of the goals and study boundaries, a methodical examination of the construction stages shown in Figure 4 was undertaken. Once the key processes were identified, data were obtained to quantify each individual process. The box on the left of Figure 4 contains the EE and EC intensities for raw materials used in producing the materials needed for the embankment, stream diversion and ponds. Direct and indirect emissions are illustrated leaving these main unit processes.

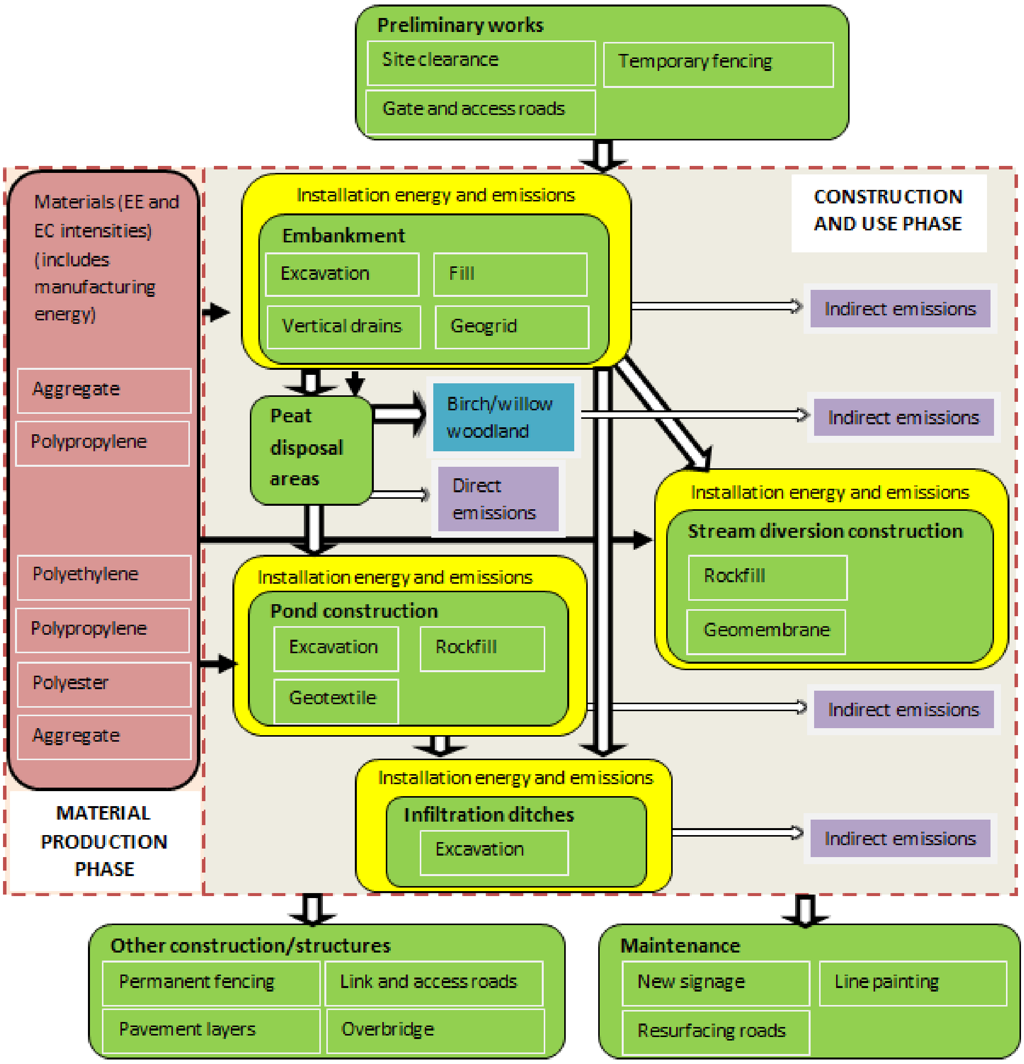


Figure 4 – Process flowchart of Scenario ER

4.2 Life cycle inventory

This section presents the collection of data for each process included in the product system, as defined in Section 4.1 and summarised in Figure 4. Where possible, data were validated by comparing them with other sources.

4.2.1 Materials, transport and machinery

Table 1 contains the life cycle inventory (LCI) of the relevant properties of the materials needed for the study. Resulting from uncertainties after product manufacture, it has become common practice to calculate EC and EE intensities for materials right up to when the product leaves the factory [21]. The aforementioned life cycle profile was adopted in this LCA, using intensities from V2.0 of the inventory [21].

The materials employed in Scenario ER (i.e. as constructed) include aggregate, vertical drains, and a geogrid. The 8 m long, 100 mm by 4 mm polypropylene band drains (permeable plastic cores wrapped in filter membranes), installed in a triangular pattern with a centre-to-centre spacing of 1.75 m were imported from the Netherlands via the UK on average weight laden transport (Table 1). A polypropylene geogrid was used for the embankment, a polyester geotextile employed for the permeable separating pond liner, and a linear low-density polyethylene (LLDPE) impermeable geomembrane for the stream diversion. These geosynthetics were assumed to have been imported from England by road and sea over distances given in Table 1. A bulk density of 1000 kg/m^3 was adopted for the peat, which was assumed to be transported an average distance of 1.07 km on a rigid truck (>17 tonnes), a distance equal to half the contract length. The trucks were fully loaded to the peat disposal area and empty on the way back. Table 2 gives fuel consumption rates for the use of diesel (UK average biofuel blend), which has an EE intensity of 38.3 MJ/l [30]. Transport distances were kept to a minimum, thereby minimising the environmental cost of transport. All transport by sea was assumed to involve average weight laden cargo ships.

Table 1 – Materials required for Scenario ER

Scenario ER									
Materials	**Density (kg/m^3)**	**EC intensity (kgCO$_2$eq/kg)**	**EE intensity (MJ/kg)**	**Distance travelled on land one-way (km)**	**Transport Vehicle**	**% Weight Laden**	**Distance travelled by sea (km)**	**One or two way transport**	**Volume (m^3)**
Aggregate	2240	0.0052	0.083	15	Rigid	100, 0*	0	Two	170000
Rockfill	2240	0.0052	0.083	15	Rigid	100, 0*	0	Two	405
	(kg/m^2)								**(m^2)**
Geogrid (PP)	0.4	3.43	99.2	204	Articulated	62	226	One	80000
Geotextile (PE)	0.3	2.54	83.1	204	Articulated	62	226	One	1969
Geocomposite (LLDPE)	0.939	2.08	78.1	204	Articulated	62	226	One	728
Vertical drain	1	3.43	99.2	486	Articulated	62	626	One	10111

*The trucks were 100% loaded from quarry to site and returned to the quarry empty

Table 2 – Fuel consumption rates for heavy goods vehicles and cargo ships [30]

Transport	**% Weight Laden**	**Payload (t)**	**Fuel consumption (kgCO$_2$eq/t.km)**	**Fuel consumption (l/t.km)**
Rigid truck (>17t)	100	9.41	0.146	0.046
Articulated truck (>33t)	62	11.78	0.103	0.032
Articulated truck (>33t)	100	19	0.075	0.024
Concrete mixer (>17t)	100	14.4 (6m^3)	0.096	0.030
Average cargo ship	60		0.016	0.005
			Fuel consumption (kgCO$_2$eq/km)	**Fuel consumption (l/km)**
Rigid truck (>17t)	0	0	0.959	0.303
Articulated truck (>33t)	0	0	0.860	0.272

Since the top pavement layers are not being considered part of the study, machinery such as pavers and compactors were not included. The EC and EE of machinery are difficult to estimate due to the large variety required in building a motorway. For the purpose of this scenario, only the EC and EE of excavators and band drain rigs were examined (Table 3).

Transport of machinery to site was not calculated as these values would be similar regardless of the ground improvement method considered.

Table 3 – Fuel consumption rates and rates of work for Scenario ER

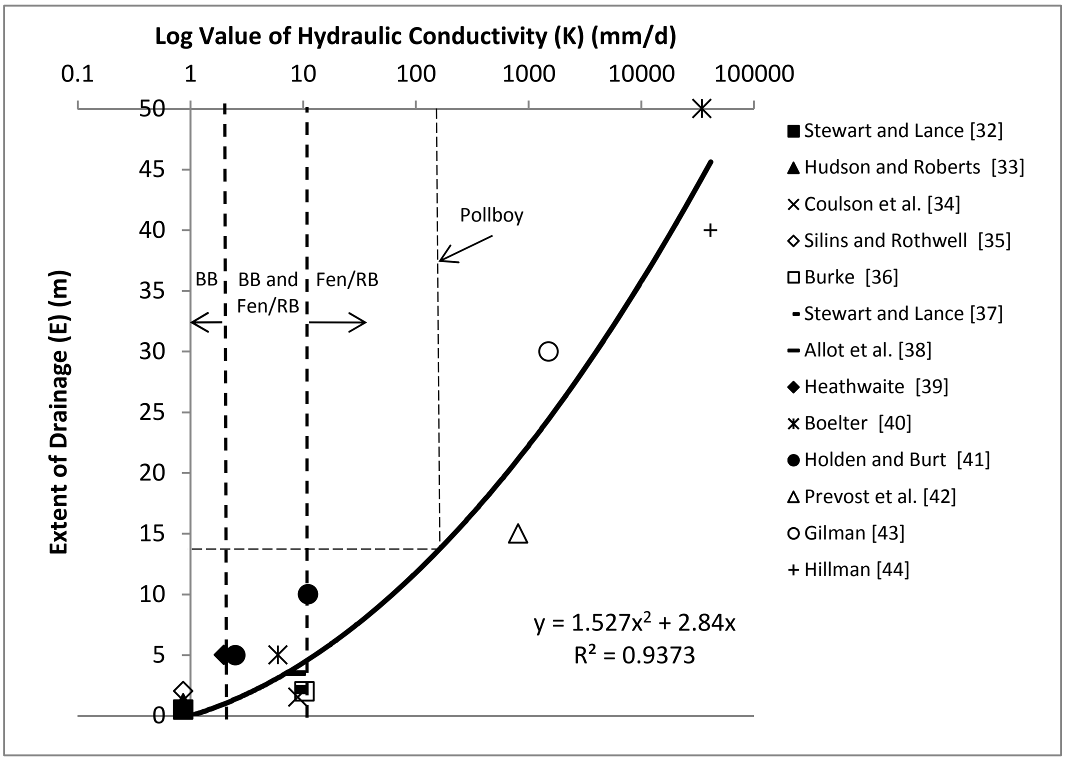
Machinery	Fuel consumption (l/hr)	Rate (m^3, drains/hr)	Amount (m^3) (drains)
21 tonne excavator	16	100	135173
Band drain rig	45	87.5	16852

4.2.2 Drainage

The lateral extent of drainage (E) due to road construction (demarcated in Figure 3) was calculated by using Eq. 1, which was based on 16 previous studies relating E to hydraulic conductivity (K) (Figure 5). The equation represents an update by the authors of this paper upon a linear fit proposed by Nayak *et al*. [24] to eight of these studies.

$$E = 1.527\log^2(K) + 2.84\log(K) \quad (1)$$

In Eq. 1, the unit of E and K are m and mm/d respectively. Using Eq. 1 and an average hydraulic conductivity of 200 mm/d (calculated from site investigation data), the extent of drainage was estimated to be 14.6 m from ditches, ponds and any other excavations. However, the extent of drainage has limited relevance for already-drained bogland, and the area will continue to be a net source of greenhouse gases regardless of construction. This drainage equation will, nonetheless, be used in Section 6.6 to calculate the environmental impact if the drained bogland had been undisturbed. CO_2 and CH_4 are accounted for in EC calculations but not N_2O emissions, which are deemed negligible from oligotrophic peatlands [31].



*BB=Blanket bog, RB=Raised bog

Figure 5 – Plot of extent of drainage against hydraulic conductivity

4.2.3 Drainage systems

Depending on the peatland type, peat depth, slope and type of ditch/pond, ditches and ponds may stay functional for decades or may deteriorate and fill with vegetation within 10 years of installation [45]. High CH_4 fluxes from drainage ditches and ponds in a temperate climate have been reported by Hendriks *et al*. [46], in particular nutrient-rich ponds and ditches. Clogged ditches consisting of algae and other vegetation that are not regularly maintained will tend to produce higher CH_4 emissions [45], exemplified by the ditches at Pollboy (Figure 6). Emissions can also be high from turbulent water due to the thinner boundary layer between the water and air interface [45]. For this study, it is assumed that only the base of infiltration ditches is covered with water all year round, which will compensate for periods when higher levels are recorded in winter or when lower or no water levels are recorded in summer. In contrast, the ponds are assumed to have a 0.25 m head of water all year round. CH_4 emissions depend primarily on air temperature, water level, speed of the moving water and vegetation [45, 47].

Studies of gas emissions from ditches and ponds in temperate, boreal and Mediterranean climates reported in the literature were examined. The highest emissions, 61.5 $tCO_2eqha^{-1}yr^{-1}$, were from a site in a Mediterranean climate because of higher temperatures and a higher decomposition rate [48]. Table 4 summarises previous studies, some of which include fens, which tend to have higher emissions than ombrotrophic peatlands. As the Pollboy section contained plants that are considered a fen species (due to the underlying marl soil), the studies were deemed adequate for use. Emission rates in a temperate climate ranged from 12.7 to 27.3 $tCO_2eqha^{-1}yr^{-1}$ (Table 4), thus an average emission rate of 20 $tCO_2eqha^{-1}yr^{-1}$ was assumed for the ditches and ponds at Pollboy for the 120-year life cycle.

Table 4 - Emissions from drainage ditches in a temperate climate

Study	**Peatland (Nutrient status)**	**Total ($tCO_2eqha^{-1}yr^{-1}$)**
Schrier-Uijl *et al*. [49]	Mesotropic/eurotrophic status	27.3
Schrier-Uijl *et al*. [47]	Eutrophic fen (intensive)	25.4
Schrier-Uijl *et al*. [47]	Eutrophic fen (less intensive)	12.3
Hendriks *et al.* [46]	Restored agricultural peat meadow	12.7
	Average	**19.4 (~20)**

Figure 6 – Clogged stream diversion shown at front and peat disposal area in background at Pollboy 3 years after construction

4.2.4 Direct emissions

The loss of carbon as CO_2 from excavated peat is considered a direct emission and should be included in EC calculations [24]. Excavated peat, which has been under anaerobic conditions, starts releasing CO_2 and other gases when exposed to the atmosphere and aerobic conditions [13]. In this LCA, the percentage of carbon lost from the peat as CO_2 (C_{lost}) was assumed to be 100% because the embankments and their sides are exposed to aerobic conditions, and it is highly probable that the excavated peat will remain above the water table for the lifetime of the road. The volume of this peat will reduce as a result of primary and secondary consolidation and peat oxidation [13]. Using the average dry density (ρ_d) of 0.121 g/cm^3 and organic content (OC) of 41%, it was found that the peat had an organic matter density of 0.05 t/m^3, which when divided by a factor (F) of 2.11 gave an embodied carbon content of 0.024 tC/m^3 (0.086 tCO_2eq/m^3). The aforementioned factor refers to the mean of the range of division factors quoted by Schumacher [16], and is explained further in Section 2.1. The total CO_2 released EC_{peat} (tCO_2eq) from the volume of excavated peat (V_{peat}) for the 120 years was estimated at 11670 tCO_2eq, (Eq. 2).

$$EC_{peat} = \rho_d \times V_{peat} \times (1/F) \times (OC/100) \times (C_{lost}/100) \times (44/12) \qquad (2)$$

Table 5 demonstrates why it is plausible that 100% of the peat's carbon may be released over the road's 120-year life cycle. According to this analysis, peat will have released all its carbon as CO_2 in 61 to 67 years at an emission rate of 20 $tCO_2eqha^{-1}yr^{-1}$ [26], or, as calculated similarly, in 123 to 134 years at an emission rate of 10 $tCO_2eqha^{-1}yr^{-1}$, which is typical of a drained peatland [50].

Had the removed peat from the road and associated drainage systems not been disturbed, it would have produced emissions. This has to be factored into net direct emissions because the focus is the environmental impact of the road, not the natural emissions that would have occurred in the absence of construction. Therefore, after subtracting the CO_2 from these excavated peat areas, the total net direct emissions were 10885 tCO_2eq (Table 6 and Section 4.2.5).

Table 5 – Calculating the duration it takes the excavated peat in the peat disposal areas (PDAs) to release all their carbon as CO_2 at an emission rate of 20 tCO_2eqyr^{-1}.

	PDA1	PDA2	PDA3	Total
Area (m^2)	51000	14805	27500	93305
Max. Vol. of peat (m^3)	94080	29610	50422	174112
Vol. of peat (m^3)	73040	22988	39145	135173
EC of peat (tCO_2eq)	6306	1985	3379	11670
Rate (tCO_2eq/yr)	102	29.6	55	
Duration to emit (yrs)	61.8	67.0	61.4	

4.2.5 Indirect emissions

Indirect emissions are related to emissions from land construction activities. These include ponds, ditches, peat disposal areas and the roadway itself. As outlined previously, the three main types of lands existing in the area surrounding the road are cutover bog, wet fields (grassland) and former bogland that has been reclaimed for agriculture, along with other land types of small area, including broadleaf plantation and made ground. Because of the various land-use types surrounding the Pollboy section, it was decided to divide the road section into two land type classifications to simplify calculations. The surrounding land was assumed to be all drained peatland grassland, except from Ch. 52930-53530, which was considered to be a cutover raised bog. Limited gas studies on emission factors from land types have been performed in Ireland, so where applicable Tier 2 country-specific emission factors were used. However, in cases where there were insufficient studies on a particular land type, emissions factors were taken from the IPCC (Table 7).

Although the water table lay below the peat layer (Figure 2), there were some pools on the cutover bog. Post construction, it was expected that a small amount of further peat drainage would occur in this area as a result of the road's drainage system, which may cause these pools to disappear. Had the surrounding peatland been undisturbed and not drained, the road's drainage system would have had a much higher impact on indirect emissions, and the peat would have lost its ability to store carbon due to peat drainage. The amount of carbon which could have been sequestered over the life cycle had the road not been built is called the carbon-fixing potential; in this study, it was zero as the site was already drained.

As a restoration technique, birch/willow woodlands were planted on peat disposal areas to blend in with the surrounding area. Birch/willow woodlands have a low yield class and, consequently, soil emissions are greater than the CO_2 uptake by the woodland. Soil emissions are accounted for to an extent in direct emissions; but once all the CO_2 in the excavated peat is emitted, the peat underneath the peat disposal areas will begin to release CO_2 for the remainder of the life cycle and is accounted for in indirect emissions (Table 8). Reported CO_2 soil emission losses and CO_2 uptake from naturally regenerated woodlands range from 15 $tCO_2eqha^{-1}yr^{-1}$ and -6 $tCO_2eqha^{-1}yr^{-1}$ at a drained peatland site in Sweden [51] to 26 $tCO_2eqha^{-1}yr^{-1}$ and -8 $tCO_2eqha^{-1}yr^{-1}$ at a woody, minertrophic fen site in Ireland [26]. Soil emissions from fens tend to be higher than from ombrotrophic bogs because the residual peat may be more decomposable [26]. Therefore, an average emission factor for soil of 20 $tCO_2eqha^{-1}yr$-[1] and an average carbon uptake of -7 $tCO_2eqha^{-1}yr^{-1}$ were assumed in this study as there were some fen species at Pollboy. A breakdown in calculating the EC for restoration is shown in Table 8, which is then used to estimate the total indirect emissions (Table 6).

Another loss of CO_2 not accounted for in this study comes from dissolved organic carbon (DOC) and particulate organic carbon (POC) leaching from the peatland (fluvial outputs), which will increase due to ditch construction and further drainage [52]. However, this is difficult to quantify and varies dramatically from site to site. Limited studies have been performed, although no emission factors have been published by the IPCC.

Table 6 – Breakdown of indirect emissions for Scenario ER

	Area (m^2)	**% comprising drained peatland grassland**	**Cutover bog (%)**	**Emissions (tCO_2eq) with the road built**	**Emissions had the road not been built (tCO_2eq)**	**Indirect Emissions (tCO_2eq)**
Ponds	1656	0	100	397	-28[2]	397
Ditches	3890	32	68	934	-58[2]	934
Peat disposal areas	93305	0	100	2886[1]	-1552	-1552
Road	55640	72	28	0	-699[2]	0
Total				1331	-1552	**-221**

[1] Restoration Emissions = Figure will go into restoration category.
[2] Already accounted for in direct emissions. Double Counting otherwise (11670-699-28-58=10885tCO_2eq)

Table 7 – Emission factors for various land types

Land type	**Tier**	**CO_2 uptake ($tCO_2eqha^{-1}yr^{-1}$)**	**CO_2 loss ($tCO_2eqha^{-1}yr^{-1}$)**	**Reference**
Ditches/Ponds	2		20	Table 4
Cutover raised bog	1		1.39	IPCC [22], IPCC [53]
Rewetted Industrial Cutaway	2	-0.5		Kiely *et al.* [54], Koehler *et al.* [12]
Drained peatland grassland	1		0.917	IPCC [55]
Forest peatland (Sitka Spruce)	2	-30	20	Wilson and Farrell [26], Black and Farrell [56]
Naturally regenerated birch/willow woodland	2	-7	20	von Arnold *et al.* [51], Wilson and Farrell [26]

Table 8 – Net CO_2eq broken down for restoration emissions

	PDA1	PDA2	PDA3	Total
Remaining Years (yrs)	58.2	53	58.6	
Soil Emissions (tCO_2eq)	5934	1569	3220	10723
Uptake over 120 years (tCO_2eq)	-4284	-1244	-2310	-7838
Net (tCO_2eq)	1650	325	910	**2886**

4.2.6 Forest and vegetation

No significant forest felling or clearance of vegetation occurred. However, if the amount of felling is known, the EC for these clearfelled trees should be calculated. Undoubtedly, some vegetation clearance took place, which also has an EC factor but was not included [25].

4.2.7 Slope stability

A slope stability risk assessment was deemed unnecessary in this study. The site had an average annual rainfall for the west of Ireland, a slope angle of less than 0.5° and is in an area not known for peat failures. Therefore, a factor of safety on indirect CO_2 emissions is not needed, which would have, if employed, accounted for peat debris from peat failures drying and releasing CO_2 [57].

Peat failures along the sides of the peat excavation prior to backfill and in peat disposal areas are assumed to be included in the total CO_2 emissions in the excavated peat EC figure. The extent of side collapse can, in general, be limited by experienced contractors who maintain the backfill close to the face.

5 Environmental impact assessment in the LCA

5.1 Case study

As a result of the excavate-and-replace (Scenario ER) ground improvement method used at Pollboy, the section's EC and EE totalled 8047 tCO_2eq/km and 25487 GJ/km respectively (Table 9). 62% of the total EC came from CO_2 released from the excavated peat (Figure 7), highlighting the significance of how excavated peat is managed. The restoration measure undertaken also showed a big loss at 16%, which could have been reduced substantially had alternative measures been taken. Materials at 66% accounted for the bulk of energy consumed, followed by transport at 32% and machinery at 1.8%. The order of EE contributions calculated are in agreement with other studies such as Chau *et al.* [9], based on a rail tunnel construction, where EE of materials for one construction scenario was also the highest contributor at 82%, followed by transport and machinery at 10% and 8% respectively.

Table 9 – Breakdown of total EC and EE for Scenario ER

	Scenario ER			
Factor	**EC (tCO_2eq)**	**Percentage (%)**	**EE (GJ)**	**Percentage (%)**
Materials	2132	12.1	35962	65.9
Transport	1458	8.25	17612	32.3
Machinery	80	0.45	968	1.77
Carbon Fixing Potential	0	0		
Direct emissions	10885	61.6		
Indirect emissions	-221	1.25		

Vegetation/Forest	0	0		
DOC and POC leaching	0	0		
Slope stability	0	0		
Restoration	2886	16.3		
Total	17220	100	54541	100
Total (per km)	8047		25487	

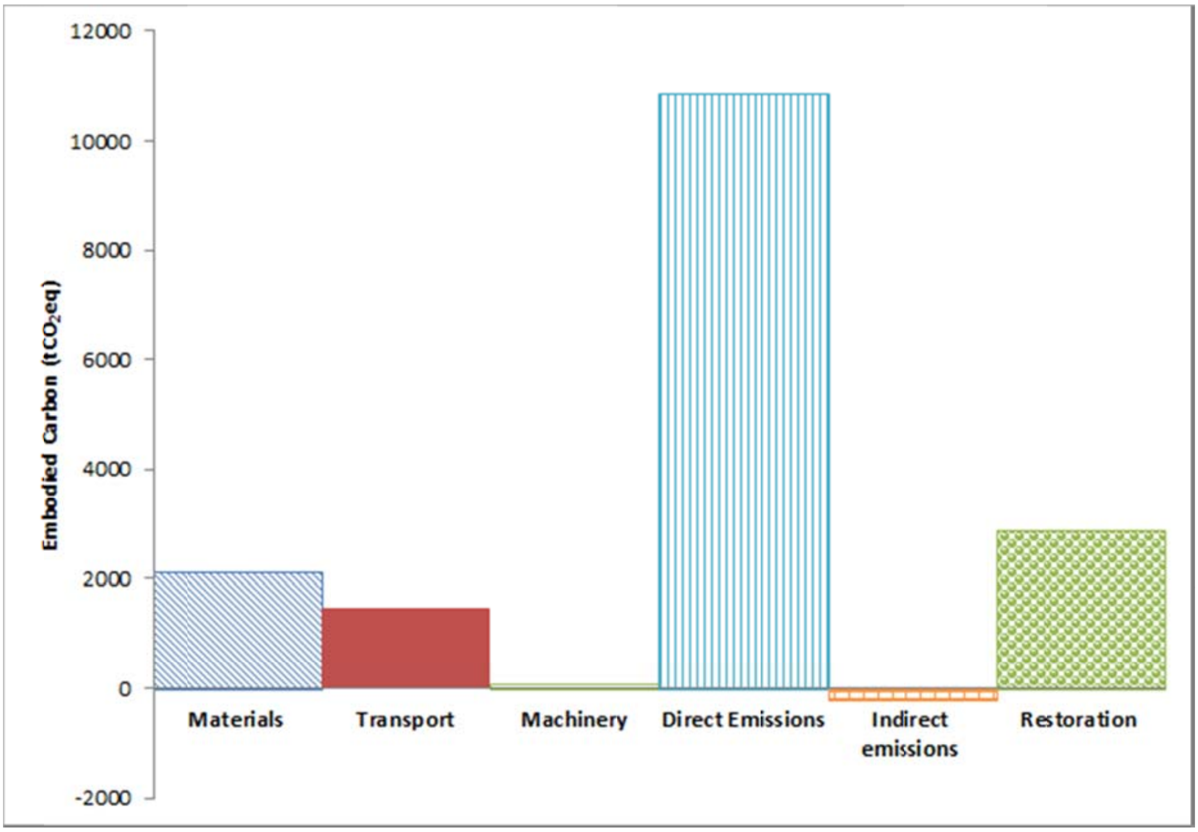


Figure 7 – Breakdown of total EC for Scenario ER

5.2 Introduction to alternative scenarios

Two alternative ground improvement scenarios were examined to evaluate the potential environmental impact of using these approaches in this case study. Scenario S used peat stabilisation to support a road embankment (Figure 8(a)), while Scenario ER+P involved a combination of peat excavate-and-replace and some piling (Figure 8(b)). In Scenario ER+P, piling is only incorporated in the zone Ch. 52300-52600, where the depth of peat is greater than 3 m along a significant stretch of road, and peat excavate-and-replace was used for the remainder of the section. In this sense, it is a hybrid scenario and should not be considered as exclusively representative of piling. Neither scenario required as many peat disposal areas, retention ponds or ditches as was required during construction in Scenario ER, as reduced quantities of peat were removed during operations. Scenario S required one peat disposal area (PDA 2), and Scenario ER+P required two peat disposal areas (PDA 1 and PDA 2).

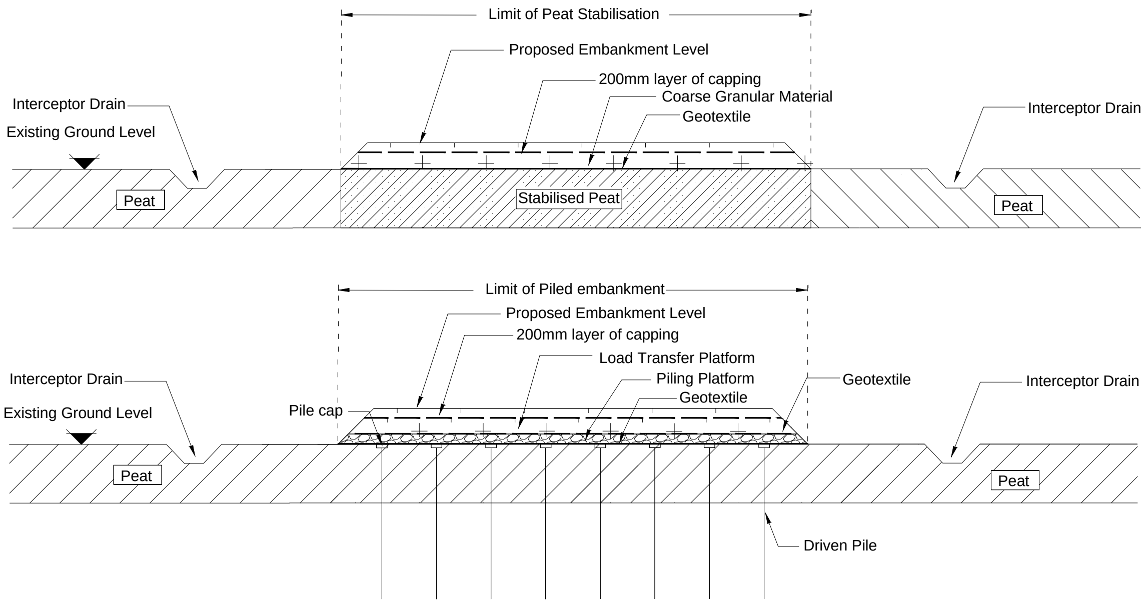


Figure 8 – (a) Typical cross sections of a stabilised embankment (b) typical cross sections of a piled embankment

5.3 Scenario S: Peat stabilisation

In Scenario S, the peat on the mainline was considered to be stabilised with a total binder content of 250 kg/m^3, consisting of 75% cement and 25% ground granulated blast-furnace slag (GGBS), proportions commonly adopted in practice. A polyester geotextile of sufficient tensile strength was placed on the stabilised platform, with the embankment placed on the geotextile. It is assumed that peat stabilisation was carried out in two sections. A surcharge 0.5 m in height was incorporated over the stabilised area (as is standard practice to maximise strength gain); once it had gained adequate strength, it was placed on the second section. The surcharge was retained as part of the embankment.

The moisture content of the peat prior to mixing was between 500% and 1000% but after mixing could be lower than 200%. Even though the water content of the peat reduces significantly due to hydration, the stabilised peat seems to retain its carbon after soil-mixing. Preliminary unpublished research at NUI Galway indicates that the binder, whether cement or a combination of cement and by-products, takes in CO_2 both from the atmosphere and what little CO_2 that is released from the peat due to carbonation. Carbonation has been widely examined in concrete where CO_2 reacts with calcium hydroxide ($Ca(OH)_2$) in the cement to form calcium carbonate ($CaCO_3$) [58]. When stabilised peat is surcharged, air voids are reduced but oxygen will continue to enter the voids to oxidise the peat. If a small amount of stabilised peat releases CO_2 and water still remains in the stabilised peat, then carbonation will occur. In this study, it was assumed that any CO_2 released from peat was absorbed by the cement in the life cycle; consequently, net emissions from stabilised peat were assumed to be zero.

Table 10 details the materials required along with their relevant transport distances. Fuel consumption rates for the machinery are shown in Table 11, which also includes stabilising machinery for dry soil-mixing.

Scenario S had a total EC and EE of 25306 tCO_2eq (11825 tCO_2eq/km) and 164364 GJ (76806 GJ/km). Figure 9 and Table 12 details the EC and EE for Scenario S. As small amounts of peat were excavated, materials in Scenario S accounted for 86% of the total EC.

Table 10 – Properties, quantities and distances for materials needed for Scenario S

Materials	**Density (kg/m^3)**	**EC intensity ($kgCO_2eq/kg$)**	**EE intensity (MJ/kg)**	**Distance travelled on land (km)**	**Transport Vehicle**	**% Weight Laden**	**Distance travelled by sea (km)**	**One or two way transport**	**Volume dealt with (m^3)**
Binder (75:25)	250	0.7357	4.61	92.5 – CEM 1 167-GGBS	Rigid[1]	100, 0	0	Two	115000
Aggregate	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	41090
Surcharge	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	13910
Rockfill	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	176
	(kg/m^2)								**(m^2)**
Geotextile (PE)	0.3	2.54	83.1	204	Articulated	62	226	One	80447
Geocomposite (LLDPE)	0.939	2.08	78.1	204	Articulated	62	226	One	728

[1]The trucks were 100% loaded from quarry to site, and returned to the quarry empty.

Table 11 – Fuel consumption rates and rates of work for Scenario S

Machinery (Scenario S)	**Fuel consumption (l/hr)**	**Rate (m^3/hr)**	**Volume of peat (m^3)**
Stabilising machinery	40	41.67	115000
21 tonne excavator	16	100	15206

Table 12 – Breakdown of total EC and EE Scenario S

		Scenario S		
Factor	**EC (tCO_2eq)**	**(%)**	**EE (GJ)**	**(%)**
Materials	21857	86.4	144855	88.1
Transport	1257	4.97	15192	9.24
Machinery	357	1.41	4317	2.63
Carbon Fix. Pot.	0	0		
Direct emissions	581	2.30		
Indirect emissions	256	1.01		
Veg/Forest	0	0		
DOC + POC	0	0		
Peat stability	0	0		
Restoration	997	3.94		
Total	**25306**	**100**	**164364**	**100**
Total per km	**11825**		**76806**	

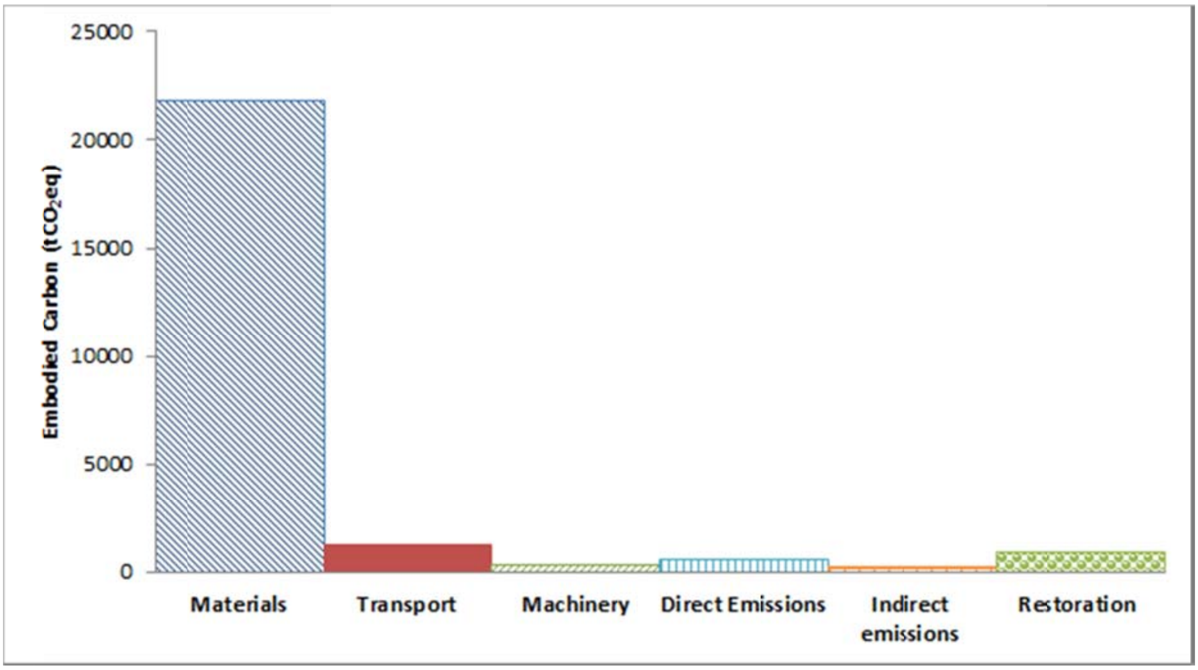


Figure 9 –Breakdown of total EC for Scenario S

5.4 Scenario ER+P: Combination of peat excavate-and-replace and piling

For Scenario ER+P, a piled embankment was envisaged over a 300 m section as mentioned. This consisted of driven precast C32/40 concrete piles, 8 m long with a cross section of 0.4 m^2 piles and 80kg/m^3 of reinforcement. The reinforcement was imported from the UK, and had an EU-27 market 3-year average recycled content of 59% [21]. Cast-in-situ 0.5 m^3 pile caps were considered, installed at a centre-to-centre spacing of 1.5 m, also containing 80 kg/m^3 of steel reinforcement imported from the UK. Above the pile caps, there is a 0.9 m thick piling platform to support machinery and a 2 m thick load transfer platform. A polypropylene geotextile was laid in the piling platform and a polyester geotextile in the load transfer platform. It is well established [59, 60] that piling has an impact on the intervening soil; ideally, any effect on indirect emissions would be captured in an analysis. However, the impact is unknown at this stage and was not included in this study.

Table 13 details the materials required along with their relevant transport distances. Fuel consumption rates for the machinery (including a piling rig) used are shown in Table 14. The concrete mixer truck was assumed to transport the concrete for the pile caps at a speed of 50 kph and a distance of 53 km. This is the maximum distance it can travel as the total time between the beginning of mixing the concrete and its final pouring should not exceed 90 minutes [61].

Scenario ER+P amounted to a total EC and EE of 17048 tCO_2eq (7966 tCO_2eq/km) and 92706 GJ (43320 GJ/km)—detailed further in Table 15 and Figure 10. The biggest contributors of EC in this case were materials at 34% due to the high EC intensity of the piles and direct emissions at 32% as a result of the relatively high volume of peat excavated.

Table 13 – Properties, quantities and distances for materials needed for Scenario ER+P

Materials	Density (kg/m^3)	EC intensity ($kgCO_2eq/kg$)	EE intensity (MJ/kg)	Distance travelled on land (km)	Transport Vehicle	% Weight Laden	Distance travelled by sea (km)	One or two way transport	Volume dealt with (m^3)
Aggregate	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	120000
Rockfill	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	277
Piles (RC 32/40)	2480	0.2226	2.162	129[3] 60[3]	Articulated[1] Articulated[1,2]	100,0 100,0	0 226	Two Two/One	6784
Load transfer platform	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	24000
Piling platform	2240	0.0052	0.083	15	Rigid[1]	100, 0	0	Two	10800
Pile caps (Concrete) (32/40 MPa) (Steel)	 2400 80	 0.132 1.4	 0.88 17.4	 53 165	 Mixer[1] Articulated[1,2]	 100,0 100,0	 0 226	Two/One	663
	(kg/m^2)								(m^2)
Geogrid (PP)	0.4	3.43	99.2	204	Articulated	62	226	One	68000
Geotextile (PP)	0.4	3.43	99.2	204	Articulated	62	226	One	12000
Geotextile (PE)	0.3	2.54	83.1	204	Articulated	62	226	One	12000
Geocomposite (LLDPE)	0.939	2.08	78.1	204	Articulated	62	226	One	728
Vertical drain	1	3.43	99.2	486	Articulated	62	626	One	8572

[1] The trucks were 100% loaded from quarry to site and returned to the quarry empty.
[2] Both transport of piles and pile caps include two-way transport except for the return boat journey for the imported steel.
[3] Precast piles were transported 129 km from the piling production plant to site while the steel needed to produce the piles was transported 60 km from the steel producer to the piling plant.

Table 14 – Fuel consumption rates and rates of work for Scenario ER+P

Machinery (Scenario ER+P)	Fuel consumption (l/hr)	Rate (m/hr)	Total length (m)
Piling rig	23	40	42400
		(m^3/hr)	Volume of peat (m^3)
21 tonne excavator	16	100	72918
		(drains/hr)	Number (drains)
Band drain rig	45	87.5	14287

Table 15 – Breakdown of total EC and EE for Scenario ER+P

	Scenario ER+P			
Factor	EC (tCO_2eq)	(%)	EE (GJ)	(%)
Materials	5986	34.4	71933	77.6
Transport	1595	9.18	19275	20.8
Machinery	124	0.71	1498	1.62
Carbon Fix. Pot.	0	0		
Direct emissions	5537	31.9		
Indirect emissions	-165	0.95		
Veg/Forest	0	0		
DOC + POC	0	0		
Peat stability	0	0		

Restoration	3970	22.8		
Total	**17048**	**100**	**92706**	**100**
Total per km	**7966**		**43320**	

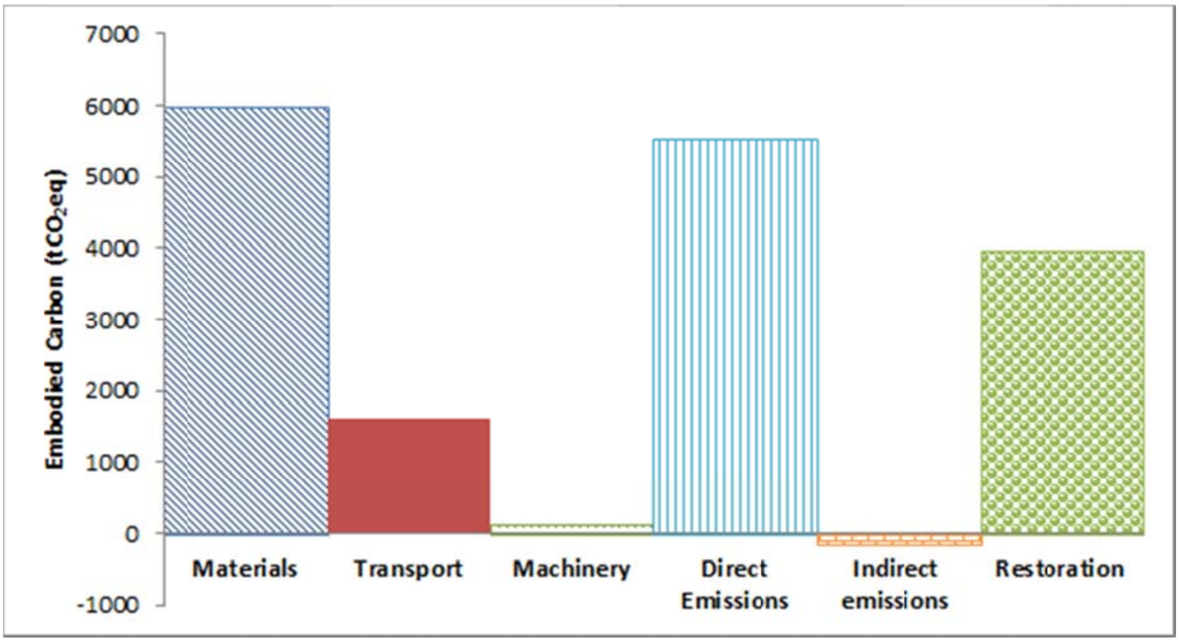


Figure 10 – Breakdown of total EC for Scenario ER+P

6 Interpretation and discussion of the results

6.1 Overview

It is important to distinguish between EC and EE in the context of road construction. For the LCA factors for materials, transport and machinery, a high EE figure gives rise to a high EC figure due to the typical use of fossil fuels as primary energy sources for these processes. This would be the case had the road not been built in peatlands. However, in the Pollboy case study, the road is built in peatlands; consequently, peat-related factors increase EC substantially, while having no effect on EE. Additional contributions to EC will include emissions from land construction activities, such as excavated peat, drainage systems, ponds and peat disposal areas. The higher the EC, the greater the on-site environmental impact, thus the greater the effect on global warming. In summary, EC is more important than EE when considering which ground improvement technique to use in construction on peat.

However, EC and EE results are both determined in this LCA, as the EE value may be used as a distinguishing factor when EC results are similar for two ground improvement methods. Furthermore, if EE results are also similar, on-site impact could then be examined in terms of land area required as well as direct, indirect and restoration emissions. Cost is obviously also a major factor in design, but is not examined in this study. When EC values are similar, caution is advised in ranking the methods as the accuracy of carbon emissions is more difficult to estimate and subject to more variability than EE results, due to the variability in peat and the uncertainties of emission factors. Consequently, it will be for the consultant to determine the accuracy of the EC figures as any total EC figure calculated will depend on how comprehensive the LCA study is (see Section 6.7).

6.2 Comparison of ground improvement techniques

Comparisons of total EC and EE for the three scenarios investigated in this study are illustrated in Figure 11. Scenario ER and ER+P had similar EC values (i.e. 17220 tCO_2eq and 17048 tCO_2eq, respectively), whereas Scenario S had an EC value of 25306 tCO_2eq. However, Scenario ER had the lowest EE (54541 GJ) compared to Scenario ER+P (92706 GJ) and Scenario S (164364 GJ). Scenario ER was, therefore, the preferred technique. The main advantages and disadvantages of each scenario are summarised in Table 17.

The EC and EE of construction materials were the predominant contributors to the overall EC and EE of Scenario S (i.e. 86.4% (i.e. 21857 tCO_2eq) and 88.1% (i.e. 144855 GJ), respectively) (Figure 11). This was mainly due to the use of a blend of 75% CEM 1 and 25% GGBS as a stabiliser. The effect of an alternative binder combination is discussed in Section 6.3. On the other hand, no cementitious material was used in Scenario ER, hence the contribution of materials to total EC and EE for Scenario ER was lower at 12.1% (i.e. 2132 tCO_2eq)and 65.9% (i.e. 35962 GJ), respectively. The construction of a piled embankment section in Scenario ER+P was an energy intensive procedure due to the relatively high EC and EE cost of reinforced concrete piles and pile caps. The contribution of materials to overall EC and EE for Scenario ER+P was therefore 34.4% (i.e. 5986 tCO_2eq) and 77.6% (i.e. 71933 GJ), respectively.

Shipment of steel reinforcement from the UK to the site in Ireland for the pile caps and piles, as well as the requisite aggregate from local quarries caused Scenario ER+P to have the highest EC (i.e. 1595 tCO_2eq) and EE (i.e. 19275 GJ) for transport. Scenario S required a lower volume of materials (binder) than the other scenarios; and as the binder was sourced in Ireland, it had the lowest EC (i.e. 1257 tCO_2eq) and EE (i.e. 15192 GJ) for transport. The global warming potential of operating machinery, however, was highest in Scenario S (i.e. 357tCO_2eq), primarily due to the stabilising machinery (i.e. 350 tCO_2eq). In Scenario ER+P, the piling machinery had a relatively high EC value (i.e. 77 tCO_2eq) compared to the excavator (i.e. 37 tCO_2eq), which was used extensively in Scenario ER.

While the optimal method will always depend on the site and construction scenario, the least preferred technique for this study was Scenario S as it had the highest EC and EE due to the high EE and EC intensities of the binder. It also had the lowest on-site and environmental impact on local surroundings of the three scenarios, as the majority of the peat remained in-situ. Scenario ER had the highest on-site and negative environmental impact on local surroundings due to high levels of peat excavation, which is reflected in the high direct and restoration emissions. These emissions accounted for 61.6% (10885 tCO_2eq) and 16.3% (2886 tCO_2eq) of the total EC, respectively, as more land was required for peat disposal areas, drainage ditches and ponds than either of the other scenarios (Figure 11(a)) (Table 16). In Scenario ER+P and Scenario S, direct emissions accounted for only 31.9% (5537 tCO_2eq) and 2.3% (581 tCO_2eq), respectively, as less land was needed. Restoration emissions for Scenario ER+P and Scenario S were 22.8% (3970 tCO_2eq) and 3.9% (997 tCO_2eq) of the total EC, respectively. The management of peat during and after construction is discussed in sections 6.4 and 6.6.

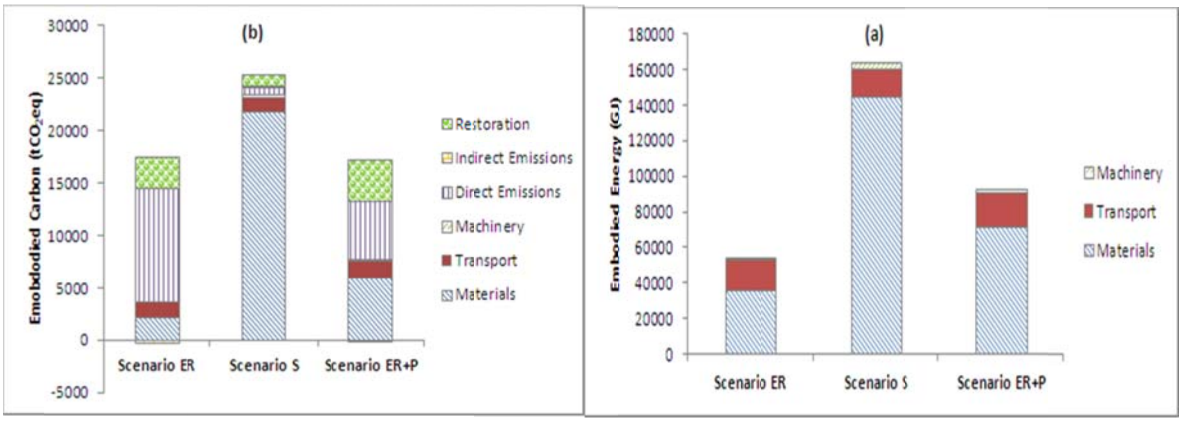


Figure 11 – (a) Comparison of total EC of the three scenarios investigated in this study, and (b) Comparison of total EE of the three scenarios

Table 16 – Land area required for some features required for the three ground improvement scenarios where the restoration scenario is a naturally regenerated woodland

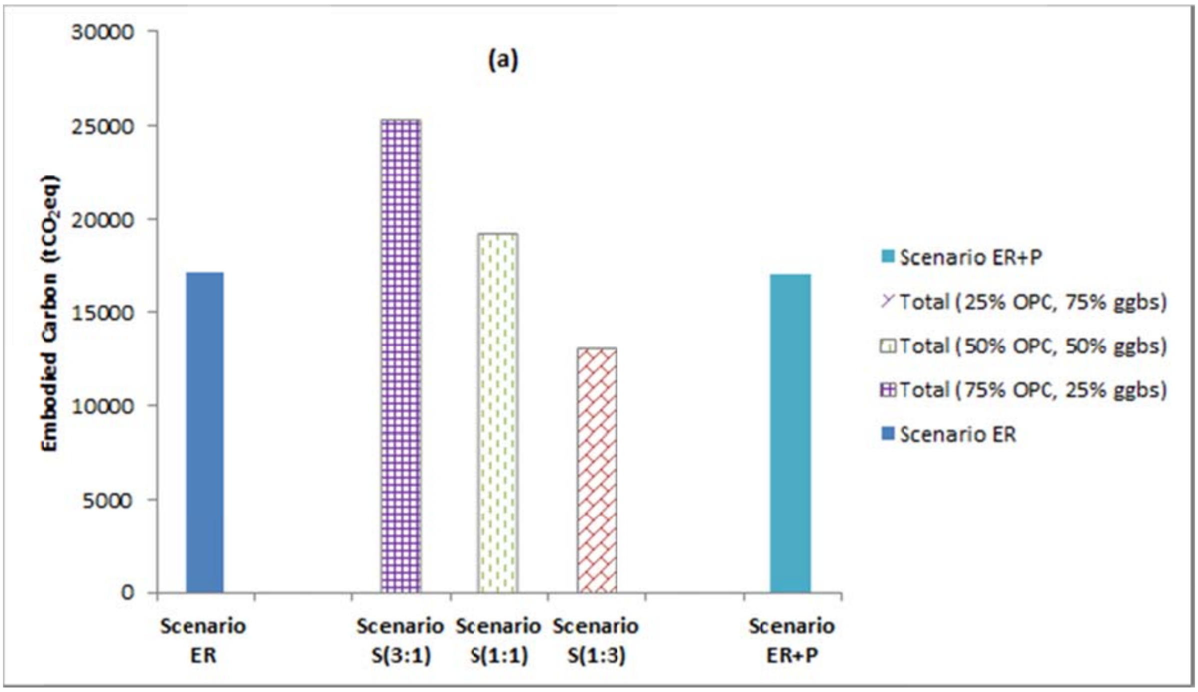
Scenario Name	PDAs (m^2)	Drainage ditches (m^2)	Ponds (m^2)
Scenario ER	93305	3890	1656
Scenario S	14805	1730	362
Scenario ER+P	65805	2945	927

Table 17 – Main advantages and disadvantages of each scenario

Scenario	Advantages	Disadvantages
ER	• Materials were of low EC and EE intensity • Emissions from transport were low as quarries nearby • Low machinery emissions	• High on-site impact • Depending on organic content, carbon emissions from excavated peat may be high
S	• Low on-site impact due to peat remaining in situ. • Alternative binder combinations have the potential to have low EC and EE intensities	• Binder had a high EC and EE intensity due to high levels of cement used • Stabilising machinery environmentally intensive
ER+P	• Where sections were piled, peat remained in situ—less environmental impact • Some materials such as aggregate were locally sourced and are of low EC and EE intensity	• High EC and EE intensity for piles due to concrete and imported steel • Piling machinery environmentally intensive

6.3 Materials – binder

Materials can represent a high environmental cost in a road construction project. In Scenario S, they amounted to 86% of total EC, with the binder accounting for 97% of this figure. Timoney *et al.* [62] showed that 1:3 cement to GGBS mixes can produce high stabilised peat strengths; therefore, it may have been possible to use less energy-intensive binders giving sufficiently high strengths. Ordinary Portland cement (OPC) has an EE intensity of three times greater than that of GGBS and an EC intensity of approximately 11 times greater than GGBS [21]. Scenarios of 1:1 and 1:3 cement to GGBS ratios were examined for the Pollboy section. Results show that EC costs can be reduced considerably to a level where the total EC in Scenario S is lower than the other scenarios (Figure 12(a)). However, EE costs are still higher than the other two ground improvement scenarios (Figure 12(b)), though in recent years cement has a decreasing clinker content, which would further reduce EC and EE costs.



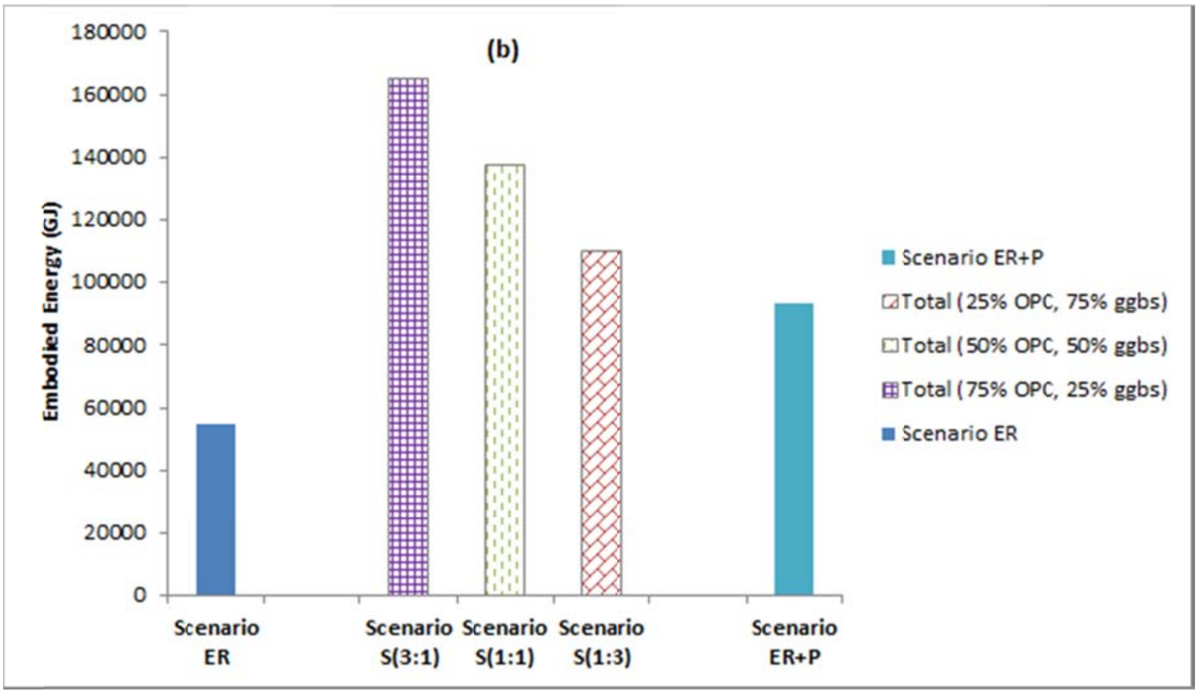


Figure 12 – (a) Bar chart showing how different binders compare with total EC (b) Bar chart showing how different binders compare with total EE

6.4 Management of excavated peat

Around 600,000 m^3 of peat was excavated along the 56 km route, 115000 m^3 of which was from the Pollboy section. Scenario ER and Scenario ER+P had significantly higher levels of excavated peat and greater on-site impacts than Scenario S. For example, the largest EC component of Scenario ER was direct emissions at 62% (10885 tCO_2eq) while restoration emissions accounted for 16% (2886 tCO_2eq). By using other restoration techniques, it is possible to reduce these percentages significantly. Rather than growing a birch/willow woodland on the peat disposal areas, which was a major contributor of CO_2, afforestation with Sitka spruce or peatland restoration could be undertaken.

By growing Sitka spruce, substantial amounts of CO_2 can be sequestered in the 120-year life cycle. Sitka spruce is a tree species that has a yield class ranging from 10 $m^3ha^{-1}yr^{-1}$ to 24 $m^3ha^{-1}yr^{-1}$ and is a source of income when it is thinned and harvested [56]. For this study, a carbon uptake emission factor of -30 $tCO_2eqha^{-1}yr^{-1}$ was used (Figure 13). The figure is based on an average of studies undertaken on Sitka spruce forests on organic soils in Ireland (e.g. -29 $tCO_2eqha^{-1}yr^{-1}$, Wilson and Farrell [26] to -32 $tCO_2eqha^{-1}yr^{-1}$, Black and Farrell [56]). Losses due to soil emissions were assumed to be at the same rate as soil emissions from birch/willow woodlands; that is, 20 $tCO_2eqha^{-1}yr^{-1}$ (Table 7). Losses due to harvesting and thinning were not accounted for.

In Ireland's current climate there is a high probability that peatland restoration will serve as a small sink. Uptake by undisturbed peatlands in Ireland has been reported from between -0.47 $tCO_2eqha^{-1}yr^{-1}$ by Kiely *et al.* [54] and -1.1 $tCO_2eqha^{-1}yr^{-1}$ by Koehler *et al.* [12]. For the current study, a lower bound long-term emission factor of -0.5 $tCO_2eqha^{-1}yr^{-1}$ was used to account for climate change, which will have a negative impact on carbon uptake. In this restoration technique it was assumed that 50% of the carbon in the excavated peat was released as CO_2 due to the agitation (breakup) of peat during transport and, more importantly, to the length of time it takes to restore a peatland, estimated at 20 years by the IPCC [55].

Depending on groundwater vulnerability, another option to deal with removed peat is to dump and bury it in decommissioned quarries and borrow pits. Two cases and two assumptions for each scenario were examined for this site where excavated peat was placed at depth and under the water table, therefore retaining much of its carbon. In the first instance, it was assumed that if the peat is kept below the water table for 120 years, 90% of the carbon would remain intact. In the second case, only 50% of the carbon in the peat would remain because the disposed peat is over and under the water table at different periods. In both cases, indirect emissions were assumed to be zero because it was assumed that emissions would be zero had the peat not been disposed of in these areas. Also factored into the aforementioned cases was the fact that due to the lack of peat disposal areas, ponds were not constructed and fewer drainage ditches were required.

The options described above to cater for the excavated peat were examined in terms of EC (Figure 13). Results show that afforestation with Sitka spruce seems to be the most promising and rewarding in terms of EC, with total EC ranging from -8532 tCO_2eq in Scenario ER to 21220 tCO_2eq in Scenario S. Burying the peat permanently under the water table and peatland restoration were also quite positive for Scenario ER, with EC totalling 4359 tCO_2eq and 7939 tCO_2eq respectively. Figure 13 shows that EC is heavily influenced by the extent of excavation of peat. When examining restoration options, it is important to use the emission factors presented as guidelines only. Further work is required to define country-specific emission factors more accurately.

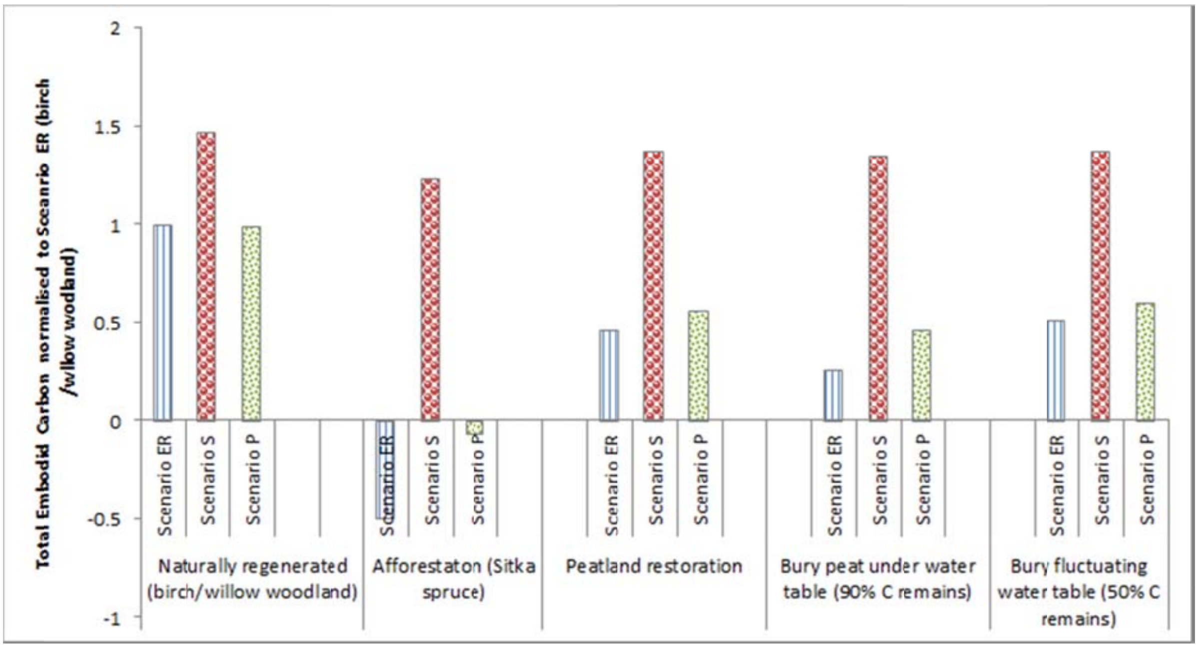


Figure 13 – Total EC showing various restoration scenarios normalised to Scenario ER (birch/willow woodland) over the 120-year life cycle

6.5 Carbon credits

Under the Kyoto Protocol, carbon credits generated from peatland restoration and afforestation can be traded as a commodity and have a mandatory and voluntary market value, with the highest potential sale value being achievable on the voluntary markets. Carbon credits were sold at prices ranging from €6.22/tCO_2eq to €6.40/tCO_2eq at the start of 2013 [63], a decrease from a high in 2008 of €25/tCO_2eq [64]. A study was carried out on Irish peatland restoration by Wilson *et al.* [65] where a carbon credit price of €20 was assumed. At this value, if a peatland had been restored at the Pollboy section as part of the construction process and the peatland had a sink of 0.5 $tCO_2eqha^{-1}y^{-1}$ for the 120-year life cycle, €1200 per hectare could have been earned.

6.6 Construction on undisturbed peatland

Had the peatland at Pollboy been undisturbed and not drained, Scenarios ER would have had a higher environmental impact due to construction, resulting in an increasing total EC. The peatland directly affected by excavation would have continued sequestering CO_2 over the 120 years had the road and drainage system not been built. The peatland would also have changed from a sink to a source of CO_2 due to the extent of drainage. The drainage system along the road and around peat disposal areas is vast, making it problematic to estimate the area affected by drainage. In essence, had there been a drain either side of the road in the peat excavate-and-replace scenario, an area of 6.25 ha would have been damaged, releasing 1040 tCO_2eq over the road's lifetime at an emission rate of 1.39 $tCO_2eqha^{-1}yr^{-1}$. Furthermore, had the peatland not been disturbed, the carbon-fixing potential would have been 375 tCO_2eq. Together, the added EC cost of indirect emissions and the carbon-fixing potential represent an additional 8% of the overall EC total of Scenario ER in this LCA.

6.7 The cost of performing a study

An important consideration for a company wishing to perform this specific type of environmental LCA would be the time and skill required and the accessibility of data. The more information a company has on a project, the more comprehensive an LCA calculation it can undertake. Once the site investigation documents are completed and the geotechnical issues are brought forward in the design stage, the data needed for this calculation will be readily available in these documents and will help in deciding which ground improvement scenario to use.

The basic components needed for the materials, transport, and machinery factors should be the most straightforward to obtain. Finding EC and EE intensities for fuel and materials, such as aggregate and cement can be obtained from databases, such as the Inventory of Carbon and Energy Version 2.0 (ICE V2.0) [21] and Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting [30]. For the peat-related factors, the following information is needed: the volume of peat excavated, the size and number of peat disposal areas required, the size of drainage systems (ponds and drainage ditches), the proposed restoration techniques and the peatland type (drained or undisturbed). Using the emission factors, extent of drainage equation and the methodology presented in this paper, an EC value for direct, indirect and restoration emissions for each scenario can be obtained. Although a user friendly tool/calculator to quantify the main peat-related factors for construction of roads on peatlands would be useful, this paper outlines ways of tackling each factor, which can be subsequently assimilated in a spreadsheet.

6.8 Other notes

Additional carbon costs not considered in this LCA include: maintenance, fencing, road markings and signs, asphalt concrete and pavement layers, subgrade preparation (compaction) and work on link and side roads and structures such as the overpass bridge at Ch. 52900. Another factor not examined was the number of workers that would be needed for each ground improvement technique. Soil-mixing would probably have required fewer personnel than peat excavate-and-replace or piling methods but would have a minimal influence on the method chosen from an EE/EC point of view. With reference specifically to peat-related factors, direct emissions would have been 23408 tCO_2eq, 2.2 times higher had the peat, for example, an average organic content of 85%, showing it to be a high-sensitivity variable. Ideally, climate change should also be accounted for; unfortunately, it was beyond the scope of this study. As temperatures rise, CO_2 emissions from peatlands will increase;

Scenario ER+P and Scenario ER will be most affected as both deal with more excavated peat and have a greater on-site impact than Scenario S.

7. Conclusions

By examining all construction and peat-related factors, the LCA methodology presented in this paper has clear potential to reduce the EE and EC of a road construction project on peat. Three ground improvement technique scenarios were assessed in terms of EE and EC, allowing the major contributions to be highlighted. Restoration techniques and other methods of reducing these factors were then examined. From the calculations presented, the main conclusions are:

- The method that was undertaken for the Pollboy contract amounted to an EC of 8047 tCO_2eq/km and EE of 25487 GJ/km. This is over 6 times greater in EC and 1.6 times greater in EE than the cost of building an asphalt pavement for a 26 m wide two-lane motorway whose EC and EE were 1300 tCO_2eq/km and 15600 GJ respectively [11]. For context, it is also over 5 times greater than the cost of building an asphalt pavement for a 28 m wide two-lane motorway (1574 tCO_2eq/km) [10] and 119 times greater than building a 3 m wide greenway (67.6 tCO_2eq/km) [66].

- The biggest EC component in peat excavate-and-replace was direct emissions from excavated peat, signalling the importance of how excavated peat should be managed.

- Scenario ER was the favoured technique for this project as it had similar EC to Scenario ER+P and the lowest EE. Scenario ER+P, ranked second, with an EE of 1.7 times greater than Scenario ER, due to the energy intensive procedure of building a piled embankment. Scenario S, on the other hand, had both the highest EC and EE and was, therefore, the least desirable solution. The EE total of materials in Scenario S was twice as high in Scenario ER+P and 4 times greater than Scenario ER due to the EE intensity of cement.

- Employing a variety of restoration techniques can substantially reduce restoration, direct and indirect emissions and provide an income from the sale of carbon credits.

- Indirect emissions can fluctuate according to the type of peatland the road is built on whether, for example, it is an undisturbed peatland, drained peatland, drained grassland peatland, or forest peatland.

- Soil-mixing in Scenario S had the lowest onsite and environmental impact on the local surroundings in direct and indirect emissions, but the binder used in stabilising the peat represented 86% of the EC total. As a result, the total EC was 1.47 and 1.48 times larger than in Scenario ER and Scenario ER+P respectively, and the total EE was 3.01 and 1.77 times higher than Scenario ER and Scenario ER+P respectively. However, the use of an alternative 1:3 cement to GGBS binder split, if appropriate from a strength viewpoint, reduces total EC by 48% and total EE by 33%.

When the potential greenhouse gases released from peat are factored in, building on peat and organic soils increases the EC cost substantially compared to building a road on mineral soils. Each ground improvement technique employed has advantages and disadvantages. By carrying out various scenarios of EC calculations on a peatland site where one of the three techniques is used or where combinations of techniques are applied, optimum EC and EE solutions can be achieved in construction on peat. It is only by analysing these outcomes that the most appropriate solution can be produced, as the preferred technique will change according to the project and site location.

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