THE USE OF FUEL CELLS FOR RAIL TRACTION IN BRITAIN: AN EXPLORATION OF THE INTERNAL AND EXTERNAL COSTS

by

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Abstract

In Britain, 40% of rail travel uses diesel trains, producing emissions contributing to climate change and air pollution. Monetisation of the negative impacts of these emissions is termed external costs. Hydrogen fuel cells offer a possible solution to reduce rail transport-related emissions. Fuel cell rail is advantageous against diesel rail for reducing emissions, and against electric rail for reducing infrastructure requirements. However, fuel cell technology is currently more expensive, and the emissions reduction potential depends upon the source of hydrogen.

This thesis aims to explore the internal and external costs of diesel, electric, and fuel cell rail (with seven hydrogen sources), to determine the option which produces the least emissions, and determine the relative financial advantage of fuel cells as an option for the decarbonisation of British rail. The findings of the analysis show that fuel cell rail with hydrogen produced by electrolysis from renewable electricity is the lowest polluting option, with no emissions at point of use or during fuel production. The financial analysis shows that this renewable hydrogen option also has one of the lowest monetary costs, on a lifetime calculation basis. The thesis assesses the adoption of fuel cell rail in Britain, as a financially viable option in the pursuit of rail decarbonisation.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations and Terms

Term	Definition
AC	Alternating Current, type of rail electrification
BOD	Burden of Disease
CO	Carbon monoxide
CO_2	Carbon dioxide
COI	Cost of Illness
DC	Direct Current, type of rail electrification
DEMU	Diesel-Electric Multiple Unit, type of diesel train
DMU	Diesel Multiple Unit, type of diesel train
Elec imp H_2	Imported hydrogen production from electrolysis, with EU average grid electricity
Elec ons H_2	Onsite hydrogen production from electrolysis, with UK grid electricity
EMU	Electric Multiple Unit, type of electric train
ExternE	External Costs of Energy methodology
FC	Fuel Cell
FCA	Full Cost Accounting
H_2	Hydrogen
HECT	Handbook on External Costs of Transport methodology
Lifetime Costs	Costs including capital and operational over defined lifetime
Loco	Locomotive unit-hauled train, type of diesel, electric or fuel cell train
NO_x	Nitrogen oxides
NR	Network Rail
OLE	Overhead Line Equipment, for rail electrification
On wind	Onshore wind renewable energy
Off wind	Offshore wind renewable energy
Overall Costs	Costs including internal and external over defined lifetime
PM/PM_{10}	Particulate Matter/Particulate Matter smaller than 10 microns
REN	Renewable energy (solar, onshore wind, offshore wind)
Rolling Stock	Any type of train
ROSCO	Rolling Stock Operating Company
Route	Defined part of rail network between departure and arrival stations

SMR	Steam Methane Reforming
SMR imp H_2	Imported hydrogen produced from steam methane reforming
SMR ons H_2	Onsite hydrogen production via steam methane reforming, with UK gas grid methane
SO_2/SO_x	Sulphur dioxide/sulphur oxides
REN H_2	Onsite production via electrolysis, with renewable electricity
train-km	Train-kilometre, distance of travel for a train
Track	The rail tracks which make up railway routes
TOC	Train Operating Company
VOC	Volatile Organic Compound (NM - non-methane)
WTA/WTP	Willingness to Accept/Willingness to Pay

CHAPTER 1: INTRODUCTION

1.1. Context and Background to the Research

Climate change is the biggest challenge facing humanity on our planet, and realisation of the need to rapidly reduce carbon emissions is evident in inter-governmental, policy, and organisational agendas. Since this research project began, the term climate crisis has begun to replace climate change as a description of the current moment in time, emphasising the criticality of the context faced by society. The United Nations Intergovernmental Panel on Climate Change announced in 2019 that by 2030 carbon dioxide (CO_2) emissions must be reduced by 45% on 2010 levels, and reach net zero by 2050. This would make it more likely that global temperature rise will be limited to 1.5°C and thereby prevent some elements of catastrophic climate change (UN IPCC, 2021). Globally, there is recognition that change needs to happen, and 190 out of 197 parties have ratified the 2015 Paris Agreement, which legally binds countries to reduce their emissions to limit global warming to the 1.5°C target (United Nations Framework Convention on Climate Change, 2021).

Transport is the largest source of greenhouse gas emissions in the United Kingdom, with domestic travel (including road, rail, and air, passenger and freight, vehicle emissions only) accounting for 28% of annual greenhouse gas emissions by source in 2018 (Department for Business, Energy and Industrial Strategy, 2020). In addition, transport emissions are the most significant source of localised air pollution, which potentially kills up to 40,000 people in the UK every year (Royal College of Physicians, 2016). Transport is also a sector that has been slow to decarbonise: in 2018, transport carbon dioxide emissions had reduced by just 3% on 1990 levels. For comparison, the energy supply sector had reduced emissions by 62% on 1990 levels, the business sector by 31%, the agricultural sector by 16%, the waste management sector by 69% and the industrial sector by 83% (BEIS, 2020). There has been a small modal shift in transportation, especially publicised in 2019, away from air travel towards rail, but this is a small scale of change and the impact this may have on reducing transport emissions has not yet been evaluated. The Covid-19 pandemic, which began in 2020, has had a significant impact on travel globally, and quite significantly in the UK. In 2020, the UK's total emissions reduced by 13% on 2019 levels, the majority of the reduction coming from a reduction in transport use. It is unlikely, though, that this will be a permanent reduction, and transport emissions post-pandemic are likely to rebound (McGrath, 2020). The Department for Transport Decarbonising Transport Plan (2021) sets out both the commitments to implementing zero-emission forms of known transport (road, rail, shipping, and air), but also the importance of transport mode shift towards active travel (walking and cycling) and public transport. Given that transport is ubiquitous in modern life, there remains a need for sustainable forms of transport. This thesis emerges in this problem space.

There has been some success in beginning to deploy ultra-low-emission vehicles (ULEVs) to reduce transport emissions. Hybrid and battery electric vehicles (HEVs and BEVs) are beginning to see widespread adoption worldwide. In the UK, although ULEVs only made up 0.8% of registered vehicles in 2019, they made up 10.9% of newly registered vehicles at the end of 2020, and between the end of 2010 and end of 2020, the adoption of ULEVs in the UK has increased by 3,427% (Hirst, 2020). The UK Government has also introduced a ban on new diesel and petrol-only vehicle sales from 2030 (DfT et al., 2020). Other vehicles such as heavy-goods vehicles and bus fleets have also slowly begun to decarbonise by adopting ULEVs (Hirst, 2020). An area of transport which seems not to be on the same trajectory of decarbonisation, is rail. Where trains run on electrified rail, decarbonisation goes in hand with power generation decarbonisation. However, within Europe this is only approximately half of rail - only Switzerland has a 100% electrified rail network (Statista Research Department, 2020). In Britain, 62% of the rail network can only run diesel trains, meaning decarbonisation must be through rail traction technology change (Office of Rail and Road, 2020a). Rail is already a relatively low impact form of transport, contributing just 2% of the UK's transport emissions, or 36.6 gCO_2e per passenger km (DfT, 2019a). However, that still represents 2.5 $MtCO_2e$ (million tonnes of CO_2 equivalent emissions) annually, and rail decarbonisation is necessary if the UK's target of net zero carbon by 2050 is to be met (DfT, 2020; Charlton, 2019). Furthermore, rail transport provides an opportunity for modal shift: that is, to move passengers away from cars and thereby reduce overall transport emissions. Not only does decarbonisation of rail benefit the greater picture of emissions reduction, but the UK Government has called for all diesel-only trains to be removed by 2040 (DfT, 2018a). The Network Rail Traction Decarbonisation Network Strategy (2020d) sets out the pathway to a net zero carbon railway by 2050, relying strongly on electrification of rail and the introduction of new traction technologies such as battery and hydrogen. This indicates the next direction of travel for UK rail, and this thesis contributes to understanding how this technology change might be achieved.

The world's first steam railways began in the UK, first as cargo transport, before opening to passenger transport. Rail instigated many of the elements of life we now take for granted, such as travelling for work or going away on holiday. Since rail privatisation in the 1990s, the railways have become highly politicised, and are a key point of difference between politicians with left and right political leanings, who (at a very simplified level) believe the railways should be publicly or privately owned, respectively. The current organisation is addressed in Chapter 2 of this thesis, although the Covid-19 pandemic has altered some existing mechanisms, and forced changes to the organisation of British rail to keep the railways running through this period whilst they were not financially viable. Beyond the ban on diesel-only rail from 2040, reducing railway emissions does not seem an important topic amongst decision-makers in the UK. Electrification is the 'best practice' for improving rail sustainability, but cancellation of electrification schemes is commonplace. For example, in 2017 the Midlands Mainline and part of the Great Western Mainline electrification programmes were cancelled due to spiralling costs, and there are rail networks in Britain that are unlikely to ever be electrified (Shirres, 2019). Between 1997 and 2017 only 60 miles of track were electrified, though since 2017 electrified rail has increased by about 400 miles. This still remains a small proportion, 6%, of the 6,120 miles of rail network yet to be electrified (Butcher, 2017a; ORR, 2020a).

Although electrification is an established technology for reducing rail emissions, it is not the only available technology. Fuel cell trains, powered by hydrogen fuel, have recently become a potential decarbonisation option. The first pilot scheme in Europe to supply normal passenger service started in September 2018, on the 100 km route between Cuxhaven and Buxtehude in Lower Saxony, Germany, running Coradia Alstom iLint fuel cell trains. This has since led to an order for fourteen more iLint trains to fully replace the diesel fleet along that line, as well as orders from other areas in Germany, and a growth in pilot projects within Europe (Railway Pro, 2020). The Coradia Alstom iLint trains cannot be used in Britain due to height restrictions caused by some of the original Victorian rail architecture (which also causes problems for electrification). There are, however, some fuel cell trains for British rail in development, with for example the

Eversholt Alstom Breeze train aiming for deployment in 2024 (Burridge, 2019; Miller et al., 2020). Fuel cell trains offer an opportunity for rail decarbonisation, as they can provide zero-emission power at point of use, but without the trackside infrastructure necessary for electric trains. This advantage has led to the inclusion of fuel cell rail as part of the Network Rail Decarbonisation Plan (2020). Rail is also beneficial for fuel cell development for transport applications, enabling to increase the demand and production of fuel cells (leading to the economies of scale necessary for widespread roll-out), whilst avoiding the infrastructure provision barriers to fuel cells for private vehicle transport.

The environmental impact of fuel cell rail depends on the method used to produce the hydrogen fuel. Globally, 95% of the hydrogen produced comes from fossil fuel sources, which emit pollutants and can be more damaging than directly using the hydrocarbons due to efficiency losses (The Royal Society, 2018). Hydrogen can however, also be produced from electrolysis of water, splitting it into hydrogen and oxygen. This method uses electricity, which can be procured from low or zero-carbon sources to produce hydrogen with low or zero emissions. The UK Hydrogen Strategy (BEIS, 2021b) sets out the UK ambition for low-carbon hydrogen production through electrolysis with offshore wind, and developments in carbon capture and storage technology.

The reason for electrification schemes to be cancelled is most often on cost grounds. There is an emphasis on cost reduction in rail, with relatively simplistic approaches to costing. For example, the high capital costs of electrification are often highlighted separately from the potential savings from lower operational costs offered by electric over diesel. Cost is an important, and often the defining, factor in decision-making processes. In the situation where we need to be improving sustainability and reducing emissions, there is the argument that sustainability should become a more important factor in decision-making, and that costs should include sustainability related costs, such as the financial impacts of emissions. That being said, decision-making is a complex and, at times, subjective process. The intent is to use a more sophisticated articulation of 'costs' as a means of evaluation within this thesis. The aim is not to alter the importance of cost in decision-making, but use it as a means to encourage reflection on what more sustainable actions might entail. In particular, this thesis uses the concept of external costs as a means of evaluating environmental impact and the idea of sustainability in a financial context. External costs, or externalities, are impacts caused by an activity, but not paid for by the one undertaking the activity. There is a wealth of literature on the subject of instituting sustainability at the heart of decision-making, and on altering the economic market to include externalities, which are touched upon further in Chapter 3. This thesis includes external cost analysis into a comparison of train technologies, as defined in the following section.

1.2. Research Focus, Aim and Objectives

This research is focussed on the internal and external Lifetime Costs of rail transport in Britain, using case studies of rail lines that pass through the city of Birmingham. With a target to decarbonise the rail network, diesel, electric and fuel cell trains are compared based on their financial viability and environmental performance in terms of emissions. The comparison is made on an Overall Cost basis, which is defined as the internal capital and operational costs (Lifetime Costs), and the external costs from monetisation of emissions impacts, over the lifetime of a train. Comparing Overall Costs enables the inclusion of a wider array of 'costs' as inputs to decisions. Emissions are evaluated and monetised, meaning translated into financial terms, using external cost analysis. Monetisation of impacts is not an exact science, and the implications and limitations of this monetisation are discussed within this thesis. The capital and operational costs are analysed based on replacing current levels of rail service provision with alternative technology. The financial viability for fuel cell rail as part of a decarbonised British rail network is thus investigated, and it is hypothesised that including the external costs into financial comparisons will provide a means on which to base the financial viability of low-emissions technologies. This investigation is based on cost, as the most important decision-making factor in rail in Britain, and emissions reduction, as the most important factor in avoiding the impacts of catastrophic climate change.

The findings from the costing work undertaken prompt three layers of additional discussion. The outcomes of the Overall Costing are used to suggest consequences for British rail decarbonisation and fuel cell development. The Lifetime Costing outcomes also lead to a broader discussion on how technological shifts arise in industry: that is, how a cost advantage results in new technologies being taken up. Theories of technological transition are briefly presented in the context of investigating the question of 'how could the conditions for a technological transition towards fuel cell rail be put in place, given the cost advantages that would result from the change?'. Finally, the discussion explores how sustainable transitions may take place, specifically in a low-carbon transport system. Altogether, this discussion considers the idea that reducing emissions and reducing costs do not have to be separate and competing objectives.

The aim of this research is to explore the dimensions of cost, both internal and external, of options for decarbonising the British rail system. The research objectives that seek to achieve this aim are:

- Selection of specific and representative case studies for examination
- Evaluation of emissions from rail
    - With the current technology
    - With potential technologies for decarbonisation (electric and fuel cell)
- Evaluation of emissions impact through external cost analysis
    - With the current technology
    - With potential technologies for decarbonisation (electric and fuel cell)
- Evaluation of internal costs - capital and operational
    - For the current technology
    - For potential technologies for decarbonisation (electric and fuel cell)
- Examination of the Overall Costs
    - For the current technology
    - For potential technologies for decarbonisation (electric and fuel cell)
- Examination of the implications for rail decarbonisation in Britain

1.3. Thesis Overview and Summary

This thesis brings together multiple elements of literature, research, analysis, and discussion, reflecting the interdisciplinary nature of the project. The literature, updated to September 2021, first moves through the historical and technical development of the British rail system and train propulsion technology, to build up the context within which the thesis operates. The literature then presents the analytical context to this thesis, aiming to formulate an understanding of the emissions evaluation and monetisation, and financial analysis methods which are used to evaluate the rail system. The next portion of this thesis roughly divides the analysis into the environmental aspects, and financial aspects, though there is some overlap. Firstly the emissions from rail are evaluated, which allows an initial comparison between rail traction technologies based uniquely on their emissions output. Costs are then brought in to the comparison, by monetising the impacts of the evaluated emissions, which gives the external costs of rail traction options. The internal capital and operational costs are then calculated for each option for rail traction, so that a financial comparison can be made on a Lifetime Cost basis. Finally, the internal and external costs are combined to give the Overall Costs of rail traction options, which gives the alternative dimension of 'costs' on which decision-making could be based. The results from the analysis lead into a discussion about setting the conditions for fuel cell rail to become part of a decarbonised British rail network. The discussion is divided into three topics: the implementation of technological transitions, the impact of the organisational structure on British rail decarbonisation, and the practical considerations of a fuel cell rail system. The thesis is wrapped up exploring the possibility of cost and sustainability elements working together in decision-making processes.

To place the chapters of this thesis into the narrative, the second and third chapters form the literature review. Chapter 2 presents the development of British rail and train technology, and Chapter 3 introduces the context, methodologies, and concepts relevant to the analysis. Chapter 4 defines the selection of case studies, and the methods used for data collection and analysis. Secondary data collection forms a significant part of empirical content for the thesis, and as a result a critical evaluation of data sources is also contained in this chapter. Chapters 5 and 6 present the analysis results. First Chapter 5 reports and interprets the results of the emissions analysis, then presents the external cost evaluation of the emissions impacts. This chapter also includes a discussion on the implications of external cost monetisation. Chapter 6 then examines the capital and operational costs in the Lifetime Costing analysis, and brings the internal and external costing elements together into the Overall Cost analysis. As the themes addressed in this thesis intertwine, the discussion and implications of the analysis findings are brought together and contained in one chapter, Chapter 7. This chapter examines the viability of fuel cell trains, through discussions on technological transition theory, the organisational structure of the British rail system and role of responsibility, and the practical consequences of implementing a fuel cell rail system. Finally, Chapter 8 concludes the thesis with a wider discussion into how the pursuit of reducing emissions and costs can work together, rather than be competing factors in decision-making.

This research presents a unique evaluation into the emissions of rail transport in a defined geographical area of Britain. Although trains are now bound by emissions standards set out in European Union directive 2004/26/EC, before 2004 this was not the case (Transport Policy, 2018). With 12 out of 27 of the companies operating trains on British rail having average rolling stock ages above 20 years, this indicates that many trains on the British network were built before the emission standards came into force (ORR, 2020a). Only one other study was found that directly examined the emissions from trains in Britain, and this focussed on the effects of the enclosed nature of Birmingham New Street station (Hickman et al., 2017). In contrast, this thesis evaluates the emissions from rail based on the levels of service provision for the selected case studies, giving the emissions profile for each case study. Furthermore, the impact of the calculated rail emissions is defined based on external cost analysis, which associates a financial penalty with the emissions from rail.

This research brings together multiple sources of information, to provide an examination of rail based on emissions, the impacts of emissions, and capital and operational costs. There is an agglomeration of emissions factor analysis, external impact monetisation methods, and financial analysis, to form an appreciation of external and internal dimensions of cost. The aim is to investigate elements which could be included into decision-making, beyond an emphasis on capital costs. Performing the analysis on a Lifetime Cost basis ensures all relevant costs throughout the lifetime of the train are correctly attributed. The Lifetime Costs give a more complete and detailed picture of costs, leading to a more informed comparison between rail technology options.

The established means to decarbonising rail is through electrification, and this thesis introduces fuel cells as an alternative that could prove beneficial to decarbonisation efforts. Transport and rail decarbonisation is in line with UK Government policy and international climate change emissions reduction ambitions. The findings from this research give comparisons between rail technologies for decarbonisation, showing how the sustainability of rail can be improved, and in a cost-effective manner. Before this can be done, the next chapter looks into the development of rail in Britain, and introduces the technologies available for rail propulsion.

CHAPTER 2: LITERATURE - TRAINS AND THE BRITISH RAIL SYSTEM

2.1. Introduction

This chapter presents an overview of the history and development of the railways in Britain, from technological and organisational standpoints. The chapter goes through the history of trains and railway infrastructure in Britain, as well as the development of rail organisation, which has informed the structural and organisational system today. The background into Britain's rail development gives the context into which this thesis attempts to evaluate rail decarbonisation. This chapter also introduces fuel cells as a new option for train propulsion technology. Fuel cell trains offer similar performance and characteristics to modern diesel trains, but without the emissions at point of use, and potentially no emissions at all, when fuelled with renewably-produced hydrogen (Ruf, 2019). The way the railways are run in Britain is likely to have a fundamental impact on decision-making processes surrounding the implementation of low-carbon propulsion methods, such as fuel cell trains. Thus, it is valuable to create an understanding of the organisational system into which the research is attempting to integrate fuel cell rail as a new form of decarbonised rail propulsion.

The ubiquitous nature of travel means there will always be a need for material and energy use to provide connectivity. The challenge now is to maintain and increase the level of connectivity and mobility achieved, whilst moving towards a more sustainable transport network, with lower emissions. Railways have received significantly less attention than other forms of transport (particularly road transport) in the literature investigating the sustainability of transport. However, the air pollution impacts of diesel trains in urban environments are beginning to be addressed (Hickman et al., 2017). Rail has a role to play in the move towards sustainable travel in two ways. Through modal shift from private to public transport, rail can reduce the overall energy use from transport, as private vehicles are less efficient per passenger. Through decarbonisation of rail, the emissions of the rail system itself can also be reduced, further reducing emissions from transport. A focus on rail is beneficial in reducing emissions, and reducing material and land use, but also beneficial to society in improving air quality, and reducing road congestion and accidents. Policy makers and organisations involved in rail provision have the task of decarbonising rail to achieve these benefits.

The current British rail network runs on a mixture of diesel and electric rail, with the recent introduction of diesel-electric bi-mode trains (which can run on both) on some longer distance and higher speed routes. The Government has made a policy decision for all diesel-only trains to be removed by 2040 (Department for Transport, 2018a). While this leaves space for diesel-electric bi-mode trains to form a significant portion of rail provision, a diesel-free network necessitates either complete electrification of the network, or the introduction of new, low-emission rail technologies. There are several options for new propulsion technologies, including biofuel, batteries (alone or in battery-electric bi-mode trains), and fuel cells. It is recognised that biofuels offer a potentially lower-carbon solution to diesel, however, there remain issues surrounding land use and limits on the scale of biofuel production, and this solution does not eliminate emissions at point of use, thus contributing to localised air pollution. The Network Rail Traction Decarbonisation Plan specifies that biofuels could have a place to reduce emissions in the interim to net zero, but that these are unlikely to be available at scale, and furthermore need to be redirected to areas with no easy decarbonisation solution, such as air travel (NR, 2020d). There is also a lack of research on biofuel for train systems specifically, so this option for decarbonisation is not considered further in this study (Rail Staff, 2019).

Battery technology is another option for decarbonising rail. Batteries can be used in bi-mode electric trains, where the batteries are charged while the train runs on electrified rail, to then be used where the line is not electrified, or to fully power the train. The hybrid technology has potential, and is beginning to be tested on UK rail (Zasiadko, 2020a). However, range remains an issue for battery power, with the best predicted range standing at 90 km, which limits application potential to areas with sufficient electrification to provide the necessary running and charging conditions (Vivarail, 2021; Hitachi Rail Ltd., 2021; Global Railway Review, 2018). Due to this limitation, and the focus of this analysis lies on routes which feature long stretches of non-electrified track, battery power is also not assessed in this study.

The particularities of each technology for decarbonising rail, namely rail electrification, batteries, bi-mode, and fuel cells, mean each lends itself to different parts of the rail network. The expectation would be for electrification to be beneficial in areas of high track usage, for batteries to provide power in-between electrified lines, and for fuel cell rail to be suited for more remote areas. There is potential for an efficient system made up of a mixture of decarbonised train technology options. The rail industry seems ready for the introduction of new decarbonisation technology, as developments of battery and hydrogen are beginning to be tested on UK rail, and the NR Traction Decarbonisation Strategy sets out electrification, battery, and hydrogen as the three technologies to work together for traction decarbonisation (NR, 2020). As fuel cell rail is proven in an operational environment, this would be defined at technology readiness level 9 (Fuel Cells and Hydrogen Joint Undertaking, 2020). This chapter contextualises the development of railway infrastructure, technology, and organisation.

2.2. Railways in Britain

2.2.1. A Brief History

The opening of the Liverpool to Manchester line in 1830, as the world's first steam-powered public line open to both freight and passengers, is generally regarded as the beginning of the railway age. Preceding the opening of this line, other forms of rail had existed, in the form of short private tracks for moving coal from the mines to the waterways network (Bogart et al., 2018). The 19th century saw railway construction accelerate in Britain: at the end of 1830 there were 200 km of railway constructed, by the end of 1871 the railways had grown to 20,000 km, and by its peak in the 1910s the network covered almost 38,000 km (Office of Rail and Road, 2018a). Three periods of 'railway mania' occurred in the late-1830s, mid-1840s, and early-1860s, where there was a concentrated expansion of tracks and rail companies. Figure 2.1 presents a selection of maps created by Bogart et al. (2018) using data from Cobb (2015), showing the development of railways in Britain between 1836 and 1911. This proliferation of the railways was largely uncoordinated and driven by competition between private enterprises, itself driven by lack of Government regulation stemming from the belief that competition and free markets would produce the optimal outcome. This approach, however, led to significant social costs and an inefficient system (Bogart et al., 2018). Even after numerous mergers and takeovers, there were 120 individual companies when the 1921 Railways Act was introduced (National Archives, n.d.).

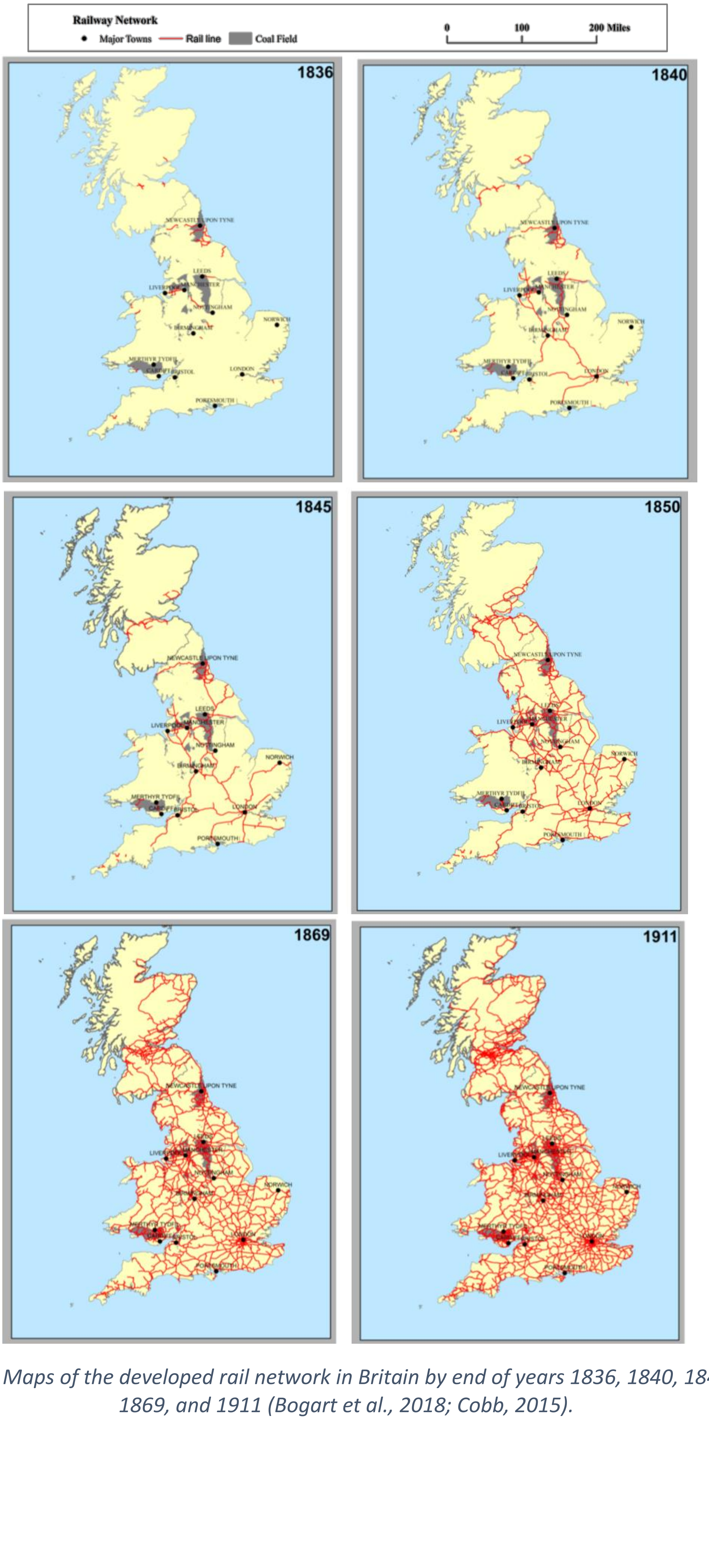

Figure 2.1: Maps of the developed rail network in Britain by end of years 1836, 1840, 1845, 1850, 1869, and 1911 (Bogart et al., 2018; Cobb, 2015).

The Railways Act 1921 implemented the first structural organisation to the railways, bringing all the independent companies into what became known as the 'Big Four' railway companies: London Midland and Scottish Railway (LMSR), London and North Eastern Railway (LNER), Great Western Railway (GWR) and Southern Railway (SR). Each railway company was responsible for a geographically defined section of the network. The next reorganisation occurred when the 1947 Transport Act brought the railways under public ownership as British Railways, which then became British Rail. The final major reorganisation happened with the Railways Act in 1993, which privatised the railways again. Since then, there have been small changes, but the structural organisation remains dominated by the 1993 Act of privatisation (Williams, 2019a). Within the period of public ownership between 1947 and 1993, the rail network underwent two major changes. In the 1960s, two reports were written by Dr Richard Beeching, recommending the closure of 6,000 miles of track, and Government investment into the upkeep of only 3,000 miles of the remaining network, with the aim of reducing railway costs (ORR, 2018a). These measures became known as the 'Beeching cuts', and resulted in the closure of 30% of rail miles at the time. The transition from coal to diesel propulsion also happened in the 1950s and 60s. Electrified rail has also been around during most of the 20th century, initially used for novelty railways, but gaining in prominence on tracks in and around London. The current rail network now covers 15,900 km, of which 6,050 km are electrified, and 1,320 km are open to freight only (Goddard, 2018, ORR, 2020a). Figure 2.2 drawn from Doe (2019), illustrates the current network (with train operating companies defined by colour and line shape).

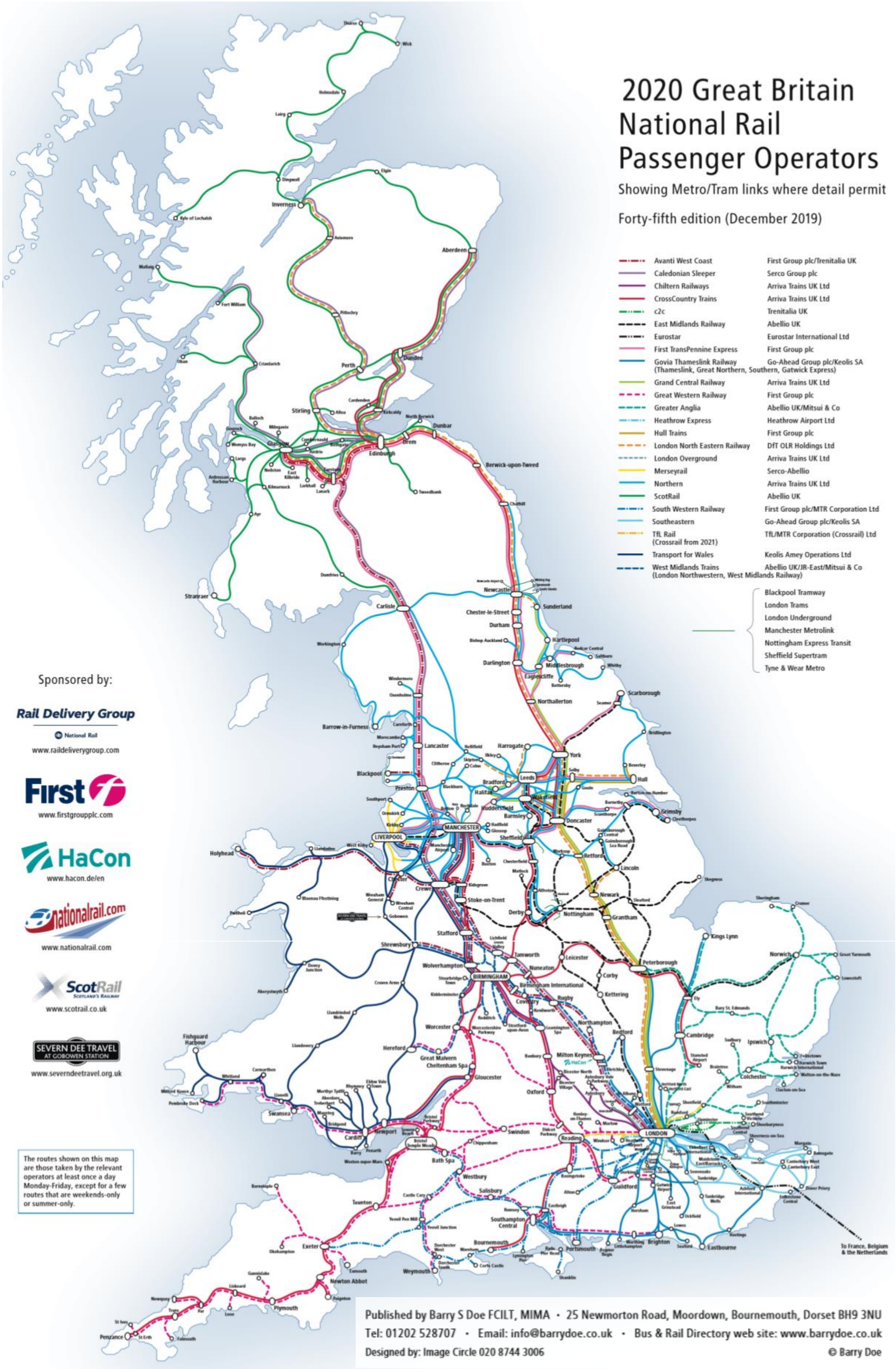

Figure 2.2: Map of the current British rail network (©Doe, 2019).

The rail network in Britain runs on a mixture of diesel-powered trains and electricity-powered trains, and a recent addition of 130 bi-mode trains within three rail franchises. The average train rolling stock age at the end of 2020 was 17.33 years, ranging from 6.96 years for the TransPennine Express franchise, to 40.58 years for the Merseyrail franchise (ORR, 2020a). There are trains built in the late 1970s and 80s in mainline use today (Kelly, 2016), but new (diesel and electric) replacement stock is being rolled out and has led to a decrease in the average rolling stock age over the past three years (ORR, 2020a). In 2019, rail travel accounted for 9% of passenger-km distance travelled in England - versus 77% for car, and 4% for bus. Since 2000, based on passenger-km distance travelled, rail travel has increased by 70%, car travel has increased by 15% and bus travel has decreased by 30% (DfT, 2019a; DfT, 2019b). 1.759 billion rail passenger journeys were made in Britain in the year 2018-19, the highest since records began in 1994, with just under 70% of those made with London and South Eastern operators, and 62% starting or finishing in London (Ramyead, 2019). 55% of rail journeys in England are made for commuting to work or education, 25% for leisure, and the rest for business, shopping or other purposes. The British network has also been identified as one of the most heavily congested in Europe, and more rail trips are made in Great Britain than any other European country, except for Germany (Williams, 2019b; DfT, 2019a). Rail freight on the other hand is at its lowest since the late 1990s, and only accounts for 9% of freight moved, despite emitting 76% less CO_2 than road freight per tonne-km (Williams, 2019b). Developing on the historical progress of rail, the current organisation and structure of the railways has become established in the last 30 years since privatisation.

2.2.2. Organisation and Structure Since Privatisation

The Railways Act in 1993 privatised the British rail network, splitting the then British Rail into two parts: the national rail infrastructure, and operation on the network. Network Rail was created in 2002 to take on the rail infrastructure, including 32,000 km of track, 30,000 bridges, tunnels, and viaducts, and thousands of signals, level crossings, and stations (Network Rail, 2019a). Network Rail was initially set up as a non-profit company, investing income directly into maintaining and developing the railways, before being made a central government body of the Department for Transport (DfT) in 2014. The privately-owned Train Operating Companies (TOCs) and Freight Operating Companies (FOCs) operate the trains on the railways, and generally the trains (rolling stock) are owned and leased by private rolling stock companies (ROSCOs). TOCs compete to run specific passenger services which are let in multi-year franchises by the DfT. Some of this is devolved, with the Scottish Government having jurisdiction over Caledonian Sleeper and ScotRail franchises, and the Welsh Assembly Government having jurisdiction over Transport for Wales franchising (Butcher, 2018; Williams, 2019a). Rail in Northern Ireland is publicly owned and operated separately from the rest of the UK, so this study focuses on rail in Great Britain specifically. Figures 2.3 and 2.4 show two diagrammatic overviews of the rail industry organisation. The first diagram is a simplified summary of organisations, while the second provides more detail of the relationships between organisations. Details on the organisations and their role and responsibilities are summarised in Table 2.1, including a summary of passenger groups, rail groups, and regulators.

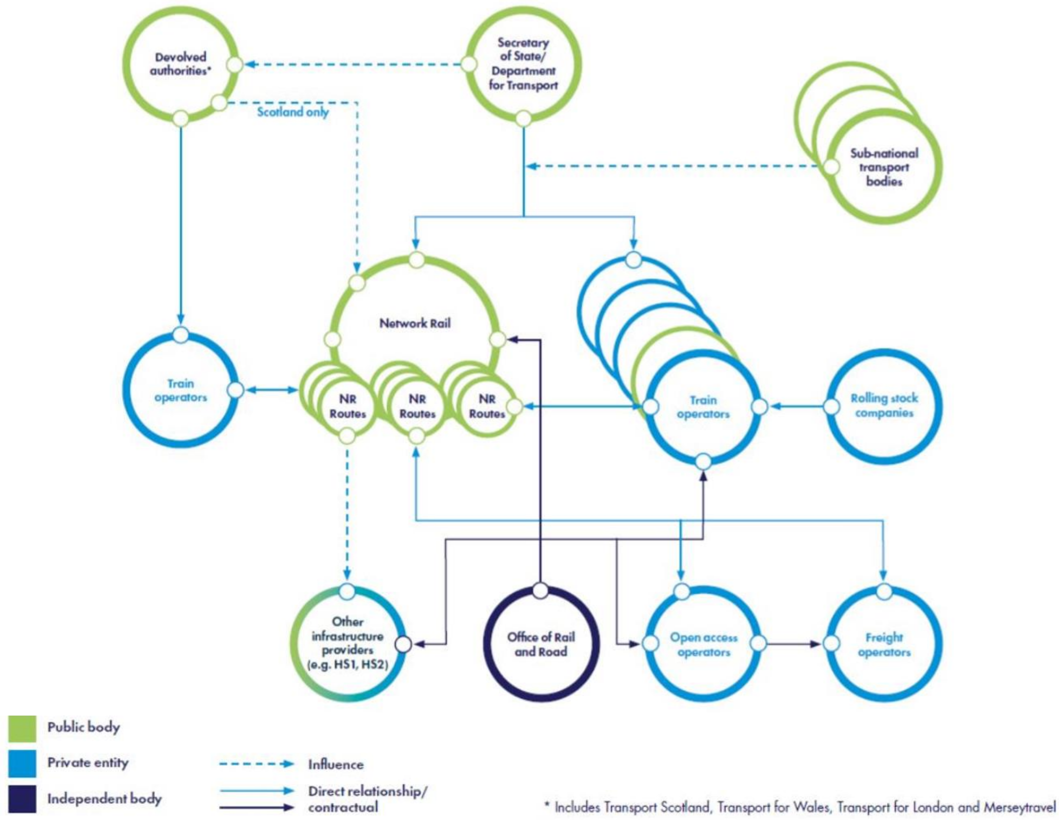

Figure 2.3: Overview of the rail industry organisation in Britain, version 1 (Williams, 2019a).

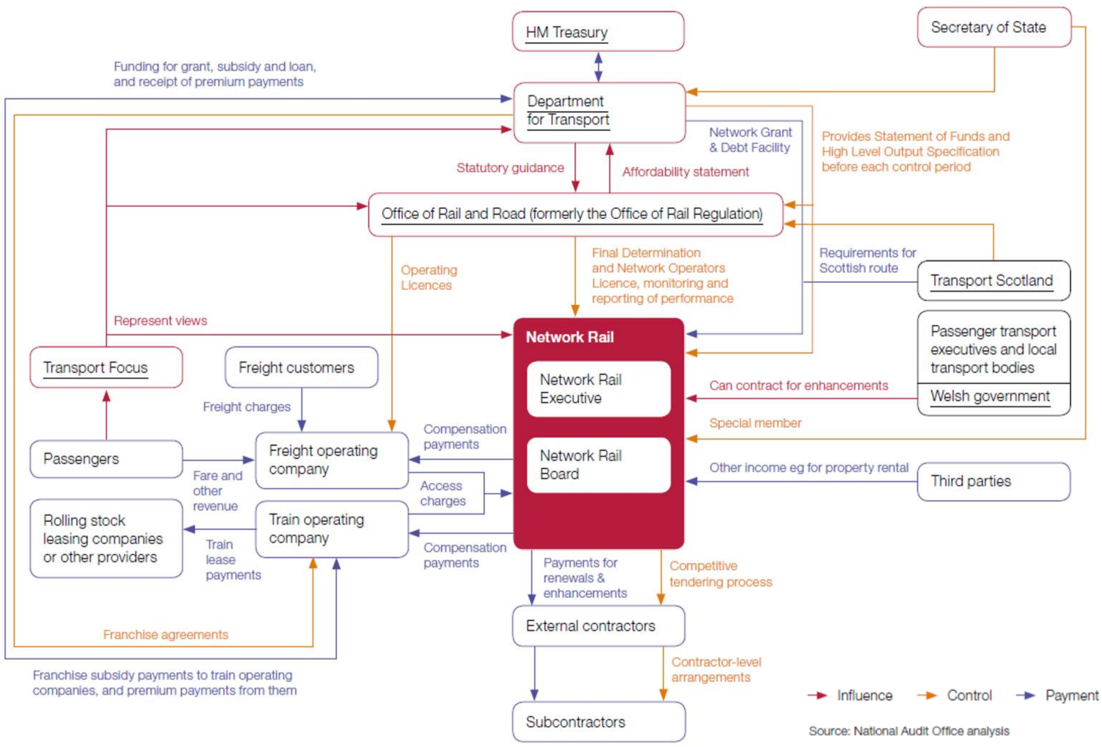

Figure 2.4: Overview of the rail industry organisation in Britain, version 2 (Butcher, 2018).

Please note: The ‘Fare and other revenue’ arrow from ‘Passengers’ should be made to ‘Train operating company’, not ‘Freight operating company’.

Table 2.1: Railway organisations in Britain (Butcher, 2018; Williams, 2019a).

Organisation	Role	Responsibilities	Responds To	Funding
DfT, Devolved Governments	Strategy planning and franchising	Strategy framework, sponsoring NR, franchising, funding	UK Gov	Treasury
Network Rail (NR)	Railway infra-structure	Timetables, operation, maintenance and development, passenger terminals	DfT, ORR (details below)	DfT, access charges, property lettings
Train Operating Companies (TOCs)	Train operation	Running passenger services, pay NR for access and ROSCOs for leasing trains, franchised stations	DfT, ORR	DfT, fares revenues, property lettings
Freight OCs (FOCs)	Freight operation	Running freight shipping, pay NR for access	DfT, ORR	Private revenues, support
Rolling Stock Companies (ROSCOs)	Ownership of rolling stock	Private sector companies owning the rolling stock leased to TOCs and FOCs	NA	Leasing revenues
Office of Rail and Road (ORR)	Rail regulator	Regulating NR and OCs, licensing train operations, oversight of charges, economic regulation, safety	Parliament	Licence fees and safety levy
Transport Focus	Watchdog representing transport users	Ensuring operators, funders, and regulators put passengers first	DfT	DfT
London TravelWatch			London Authority	London Assembly
Rail Ombudsman	Independent service for consumer complaint resolution		NA	Rail industry
Rail Delivery Group	Coordinating cross industry initiatives	Coordinate operations, settlement of passenger revenues.	Members	Membership fees
Community partnerships	Rail promotional activities and community engagement		Community	DfT and local grant funding
Rail Safety & Standards	Oversight of rail standards	Not-for-profit non-statutory body	NA	Membership fees

The infrastructure and operations of the railway are funded from a mixture of public sector grants, and revenues from various sources, as detailed in Figure 2.4. The majority of public funding goes to Network Rail to maintain and develop the rail network. The DfT is also responsible for providing subsidies to some TOCs, to enable rail provision to more remote areas with low passenger demand, which would otherwise be unprofitable (Butcher, 2018). The payment procedures between entities involved in rail, demonstrated in Figure 2.4, can become quite complex, with payments going back and forth between the DfT, devolved Governments, TOCs, ROSCOs, Network Rail, passengers, customers, and third parties - described by the Adam Smith Institute as ‘a bewildering series of money transfers’ (Haylen, 2017). This complexity, the franchising system, and the separation of rolling stock ownership and operation, results in little economic incentive for improvements such as increased fuel efficiency in the rail system as a whole. For example, in the situation where fuel efficiency improvements, and hence lower running costs, are beneficial to the TOCs, but the higher upfront costs associated with a more efficient vehicle are taken on by the ROSCOs, this can result in a resistance to improvements due to a lack of financial incentive.

In September 2018, a review into the structure of the rail industry and the way services are delivered was commissioned, led by an independent chair, Keith Williams. The aim of the Williams Review was to ‘put customers first’ in a redeveloped rail transport system. Following several delays to the original autumn 2019 deadline, the results of this enquiry were published in the Williams-Shapps Plan for Rail in May 2021. Research conducted to inform this review has focused on the context of structural organisation and passenger experience, rather than the environmental impact of rail propulsion choices (Williams, 2019b), although decarbonisation is touched upon in the final paper. Interim conclusions from this review recommended the creation of a ‘guiding mind’ with overall responsibility and accountability for running the rail network, removing DfT from day to day running of the railways, and terminating the current franchise system (Butcher et al., 2020). The final plan builds this ‘guiding mind’ into a redeveloped ‘Great British Railways’ to run and plan the rail network, with greater standardisation of the organisation, technologies, and structural and development processes. Train operation remains through private partner contract, but a simplification of the structure and clarity of leadership aims to improve decision-making ease and transparency, and improve collaboration. From a decarbonisation perspective, the Plan aims to greatly improve passenger experience and connectivity between modes, which would encourage modal shift to public transport, and a defined responsibility would help infrastructure and technology developments (Williams & Shapps, 2021). The conclusions furthermore set out the importance of long-term planning and strategy for rail, and distinguish that this would facilitate tackling specific challenges such as decarbonisation (Butcher et al., 2020).

As of March 2020, the Covid-19 pandemic has brought about and accelerated changes within the rail system. The full impact of the pandemic on the rail network remains to be seen, but it has forced the Government to step in and temporarily take on some responsibilities normally held by other entities. After the onset of the UK’s first national lockdown in March 2020, passenger numbers fell to 5% of numbers for the same period in 2019 and remained around that level for 2-3 months before increasing to stabilise at around 40% of 2019 numbers. TOC funding from passenger revenue fell accordingly. As a result, the Government moved TOCs onto Emergency Measures Agreements, which transferred all revenue and cost risk to the Government, and paid TOCs to continue running daily services to maintain the service provision for key workers.

The Emergency Measures Agreements were then changed to Emergency Recovery Management Agreements in September 2020. The function of these is similar, but additional design elements aim to begin the termination process of the current franchise agreements in line with recommendations set by the Williams-Shapps Plan for Rail. The structural organisation of rail is evolving, however this does not yet address the decarbonisation of rail.

2.3. Moving Towards Sustainable Rail Travel

2.3.1. Train Technology Development

Before the recognisable railways of today, wagons on tracks were pulled by horses, making use of terrain gradients and the reduced track friction to shift more weight than could be moved on road. The first steam powered locomotive to run on rails was introduced by Richard Trevithick in 1804, followed by Matthew Murray and John Blenkinsop's *Salamanca* in 1812, and from there development of steam trains grew into freight and passenger transport (Lumen Learning, 2021). Diesel powered trains have been in development since the 1920s, though their widespread introduction began later, in 1955 - and it took until the 1960s for the 'diesel age' of rail to really begin and for the last steam powered public passenger train service in Britain to terminate in 1968 (Bogart et al., 2018). The first electric railway was a pleasure rail opened in 1883, and a handful of lines were electrified in the 1890s and 1900s. The electrification of rail lines has been gradually ongoing for much of the 20^{th} century, particularly within the London Underground system, and the rail network surrounding London and the South East. In the 1950s and 60s the West Coast Mainline was fully electrified, followed by the East Coast Mainline in the 1970s and 80s, though this marked the end of large scale electrification projects until the 2010s. 38% of the British rail network is electrified, shown in Figure 2.5, which equates to over 60% of rail journeys due to the higher electrification and travel density around London (ORR, 2020a; Goddard, 2018). Until recently, the push for rail electrification has been mainly to provide trains which are cheaper to run and maintain, quieter, and faster to accelerate which enables greater track capacity (Nyberg et al., 2015). More recently, the issues associated with air pollution emissions from diesel train engines have become an additional factor in the argument towards electrification (DfT, 2018a).

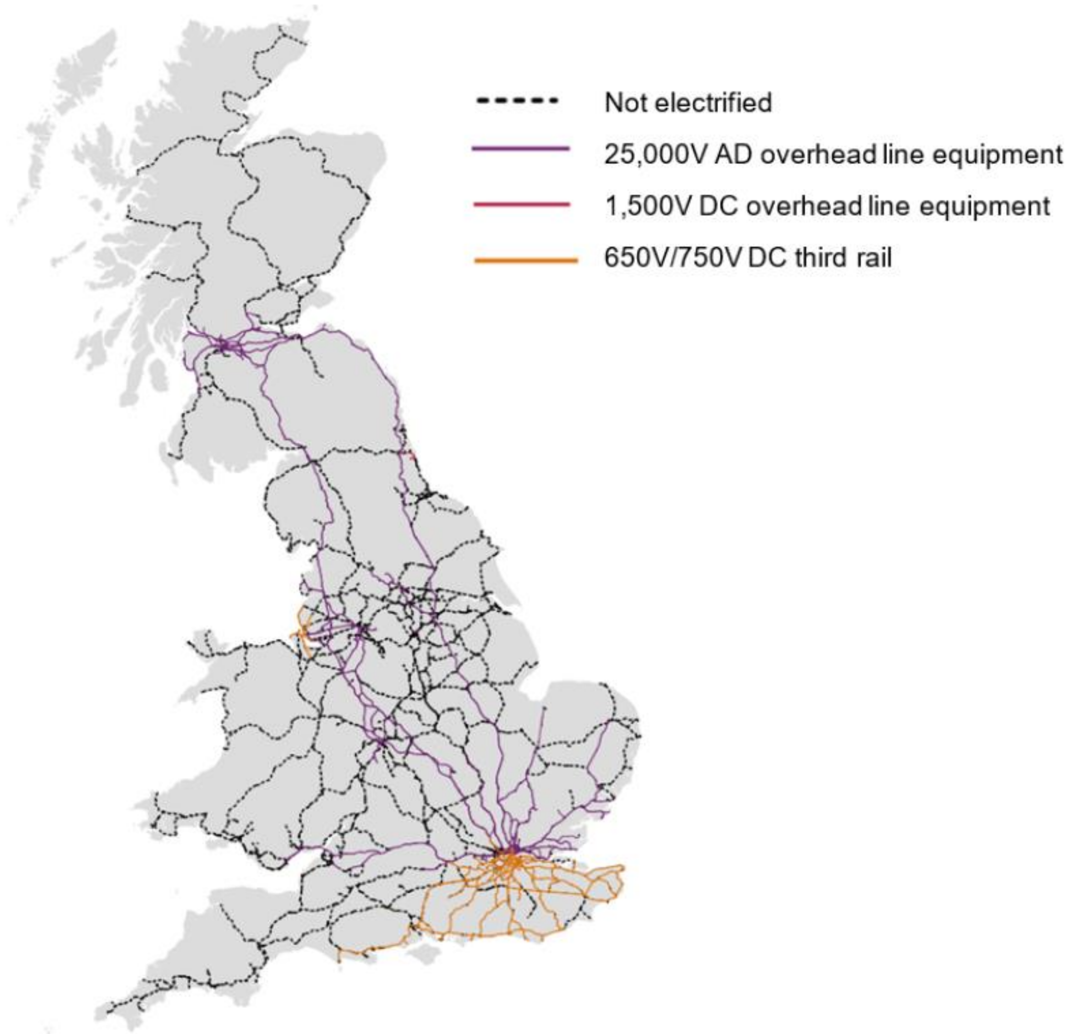

Figure 2.5: Electrified rail in Britain (ORR, 2020a).

The first electrification projects used Direct Current (DC) third or fourth rail systems, which feature an additional rail at track level to supply the electricity to the trains. This technology is susceptible to structural problems, especially in cold temperatures, making it less reliable than newer electrification systems (Rail Accident Investigation Branch, 2019). This means that in addition to new track electrification, about a third of the current electrified rail network will need replacing with updated technology in the future (green in Figure 2.5). The updated electrification technology is Alternating Current (AC), using overhead line equipment (OLE). In comparison to third or fourth rail systems, OLE lines are more reliable, can run higher train speeds, are more efficient, require fewer substations, are cheaper to maintain, and are safer for public and workers (Nyberg et al., 2015). OLE systems are not trouble-free however, and in an event where the wires are brought down, for example by storms or a falling tree, this can cause extensive disruption to the network due to the difficulty and length of repairs (Network Rail, 2019b). OLE supplies electricity through a cable structure running along and above the rail tracks, and the train is connected through arms reaching above and up to the contact wire, shown in Figure 2.6. This requires significant trackside infrastructure, which can be visually intrusive, costly, and which has to negotiate existing infrastructure, such as bridges and tunnels (Nyberg et al., 2015). Furthermore, electrification projects seem to have stalled, with the recent cuts made to scheduled projects - most notably the cancellation of the Midlands Mainline and reduction of the Great Western Mainline in 2017. There are rail networks in Britain that are likely to never be electrified, due to cost, technical barriers, and low numbers of passenger traffic (Shirres, 2019). This creates a need for an alternative to both diesel and electrification, which can provide both emissions reduction and autonomy on the current rail network. The recent Williams-

Shapps and Network Rail reports point to an expansion of electrification to meet the majority (96% for NR) of rail decarbonisation, but also that some traction will need to be met with battery and hydrogen technology (Williams and Shapps, 2021; NR, 2020d).

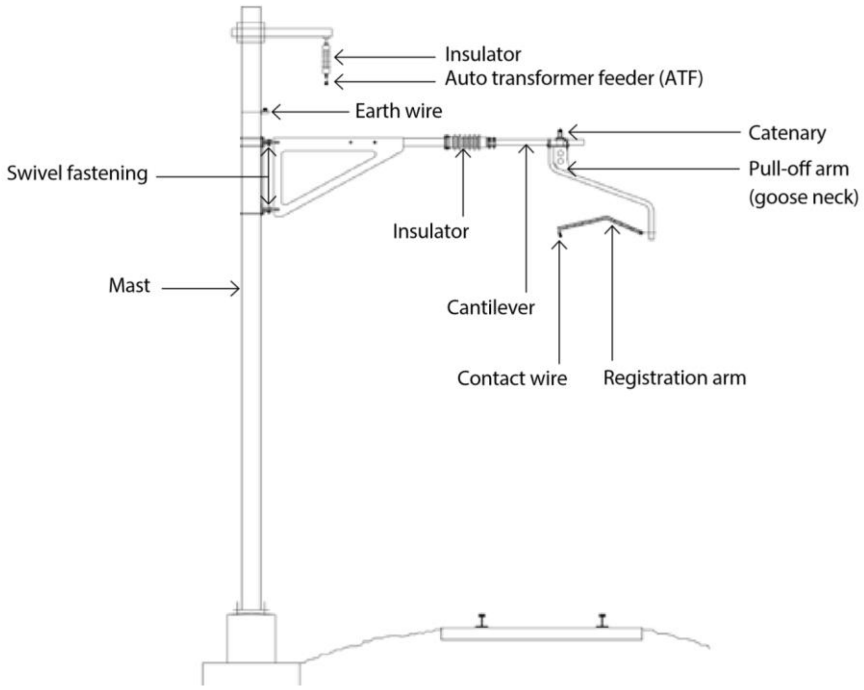

Figure 2.6: Overhead line mast, cantilever, and associated equipment (Nyberg et al., 2015).

2.3.2. Fuel Cell Rail

Fuel Cell Rail Research Developments

Fuel cell powered trains are a relatively new technology development. Although the first hydrogen rail trials in the United States and Japan occurred in 2005-2007, the first active passenger service began in 2018 in Germany, meaning relevant literature is reliant on modelling and simulation (Sun et al., 2021). Recent feasibility studies on hydrogen rail give promising results in different scenarios. Herwartz et al. (2021) assessed the feasibility of producing hydrogen from installed wind capacity adjacent to rail sites in Berlin/Brandenburg, Germany, using modelled wind production data and historical rail demand, to determine that a defined fuel cell rail system could run completely using an installed capacity of 10.5 MW and 5-day hydrogen storage capacity. Byford et al. (2020) investigated a similar energy-transport integration system in Wales, with the potential for trackside wind and solar renewable energy to provide direct energy to (future) electrified Valley Lines, though increase in capacity would necessitate some storage facility. In the US, Modovi et al. (2021) analysed the potential for long-distance intercity rail in North Carolina, simulating energy use for a fuel cell train and modelling emissions from different hydrogen production scenarios. They showed that fuel cell rail could undertake the route studied, and that the optimal hydrogen production method was using 100% renewables .

Murray-Smith (2020) studied the feasibility and energy profile of implementing fuel cell-battery hybrid rail in the UK, with a steady-state fuel cell providing the majority of power, and a battery providing additional power as needed for acceleration and inclines. The study simulated a defined test route scenario of 15 km, with typical elements of the Scottish Highland rail routes, to ensure the technology could deliver sufficient power to complete the characteristic Highlands terrain. The test defined the necessary fuel cell and battery power requirements, but pointed to potential difficulties in space requirements on UK train design due to the loading gauge. Pettit and Haden (2020) looked at the role of frameworks and standards as a significant obstacle in the implementation of fuel cell rail, especially in the context of potentially needing fuel cell rail in the short term, due to the fact that new diesel trains now would still be running in 2050-60. They identified 114 unique potential hazards with hydrogen fuel cell rail, only 7 of which are covered by the existing codes of practice, meaning there is a need for a fuel cell rail specific framework.

Logan et al. (2020) looked at the potential for fuel cell rail to contribute to net zero by 2050 in the UK, comparing fuel cell and electric rail to conventional diesel, under four National Grid decarbonisation by 2050 scenarios, and as compared to private vehicles. They used the Transport Energy Air Pollution Model (TEAM) to evaluate passenger demand and system provision, and focuses solely on CO_2 emissions for an average train, or average electricity consumption. The results show that the only option for travel (per passenger-km) that reduces emissions by 95% from 1990 levels is electric rail with the '2 degree' National Grid scenario, which defines the decarbonisation requirements to maintain climate warming to below 2 degrees Celsius. Over all electric grid scenarios, in the measurement years of 2017 and 2050, fuel cell rail produces more emissions than electric rail, but the study recognises that fuel cell rail will be required where electrification is not feasible, despite the higher emissions. Compared to diesel, both options significantly reduce emissions, and rail travel reduces passenger-km emissions as compared to private travel, even in electric cars. The study concludes that there is a need for widespread change in travel mode from private vehicles towards rail, and that with electrification renewable energy capacity needs to increase to ensure grid emissions continue reducing.

Research has also focused on the hydrogen production and refuelling side of fuel cell rail. Pons et al. (2020) studied the costs of onsite and offsite hydrogen generation through electrolysis and steam methane reforming. They determined that hubs of hydrogen production with renewable energy offers a promising zero-carbon solution, but that in urban areas there is unlikely to be sufficient room for renewable capacity. In the short term, onsite hydrogen by electrolysis is cost effective (ideal for pilot projects), but in the long-term centralised production is likely to reduce in costs and become more cost-effective. Kent (2020) determined that the Tyseley depot in Birmingham is ideal for initial fuel cell rail with refuelling infrastructure, and that hydrogen storage offers an additional function as grid-balancing, which can offset some of the higher cost of hydrogen compared to diesel. They also emphasised that the overriding aim is for UK hydrogen to be green, and producing hydrogen locally eliminates transport emissions. Guerra et al. (2021) performed a techno-economic assessment of a hydrogen refuelling station using onsite production with grid electrolysis to supply a 20-train fleet. They found that with a hydrogen production of 4,000 kg per day to supply the fleet, the investment into refuelling, production, and storage infrastructure proves a sensible investment with an internal rate of return of 15% (above the minimum acceptable 8.5%) and 9-year payback time. Piraino et al. (2021) performed a similar study for a low-usage route in Southern Italy, passenger and freight, concluding that with a daily hydrogen production of 250 kg, the production and refuelling infrastructure has a rate of return of 19% and payback time of 4.2 years. Overall, the literature on fuel cell rail still relies strongly on modelling and simulation to define feasibility in terms of energy provision and cost, however there are technical developments and implementation of fuel cell rail beginning as well.

Technical Developments

In September 2018, two of Europe's first fuel cell passenger trains, the Alstom Coradia iLint, began regular operation on a 100 km regional route in Germany, using Cummins fuel cells. The success of the iLint fuel cell trains has led to orders for 14 more trains to replace the diesel fleet on that regional route, and orders for the supply of almost 100 more iLint fuel cell trains to three other regional routes in Germany, from September 2022 (Railway Technology, 2019). Fuel cell rail testing with the Coradia iLint has also begun in Austria, the Netherlands, France, Sweden, and Poland. These exact trains cannot be used in Britain however, as they are too tall for parts of the Victorian built British network. There is work currently ongoing, though, to produce alternative designs of fuel cell trains that can work on the British network. The University of Birmingham's Centre for Railway Research and Education, along with ROSCO Porterbrook have produced a prototype fuel cell-electric bi-mode train from a refurbished class 319 Electric Multiple Unit (EMU) train, which is the first to run on a rail mainline in the UK (Burridge, 2019). Alstom with ROSCO Eversholt Rail have also produced a concept design for a fuel cell train, Breeze, based on the class 321 EMU train, which is expected to launch in 2024 (Miller, 2020). The Breeze train is concept-ready, and requiring an order from a ROSCO to begin production. The design takes up half a carriage of passenger space with the hydrogen and fuel cell, limiting its usability, but has been developed with rural Northern routes in mind. In the UK, FC rail seems to be leant on to decarbonise rail without costly electrification, but also pushed as only being usable on low-usage rural lines with speeds up to 75 mph (Oliver, 2021). A European Union study published in 2019, assessed the use of fuel cells in rail applications, concluding that there is significant market potential for fuel cell trains, due to the fact that they can perform as well as the equivalent diesel trains, without the technical constraints of batteries, and with lower cost than rail electrification in low-use areas (Ruf et al., 2019).

Fuel cells use an electrochemical reaction to produce electricity. There are different types of fuel cell defined by the materials used, operating temperature, and possible input fuels, which results in different internal electrochemical reactions. The variations between types mean they have best-suited applications, and for transport applications the low-temperature polymer electrolyte fuel cell (PEFC) is the preferred option. PEFC use hydrogen fuel and oxygen (which can be from ambient air) in an electrochemical reaction (2.1), which is also depicted in Figure 2.7 below. This reaction produces electricity (electron flow) with water as sole reaction product.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad \ldots (2.1)$$

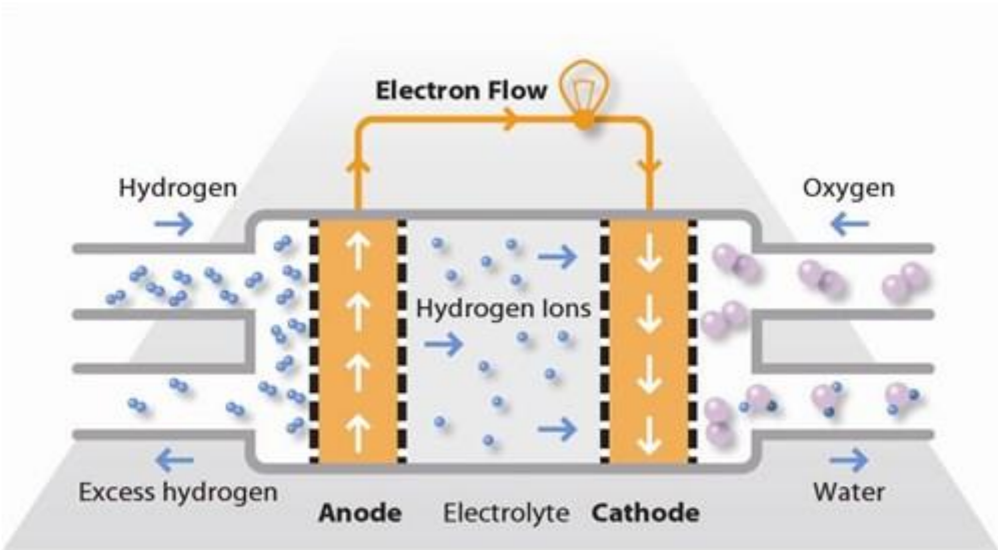

Figure 2.7: Polymer electrolyte fuel cell electrochemical reaction (Fuel Cell Technology, 2019).

In a fuel cell train, hydrogen is stored as a compressed gas, and used with oxygen from the ambient air in a PEFC to produce electricity, which drives the electric traction motor. Batteries are also used to store excess electricity from the fuel cell, and to make use of regenerative braking to improve efficiency (Hillmansen et al., 2019). The Alstom Coradia iLint, as shown in Figure 2.8, stores the hydrogen and fuel cell at the top of the carriages, and the batteries, auxiliary converter, traction inverter/converter, and traction motor beneath the carriages (Alstom, 2019). This is where the height difference becomes an additional challenge for British rail, and designing the placement of all necessary equipment without compromising on passenger space is the key step in acquiring fuel cell trains in Britain (Burridge, 2019). No trackside infrastructure is required for these trains, only alternative refuelling systems (which work comparably to diesel refuelling), and hydrogen storage capacity at train depot sites. The current iLint contract in Germany includes maintenance and the supply of hydrogen for 30 years, which helps to overcome implementation reluctance due to hydrogen supply concerns (RT, 2019).

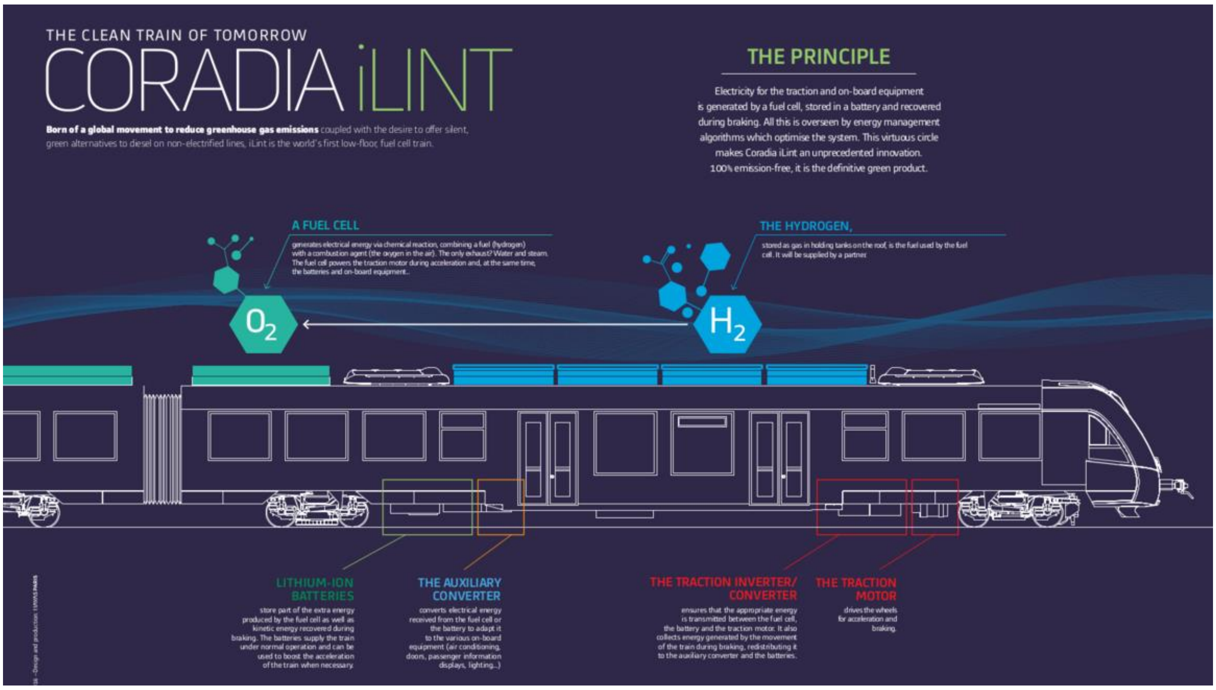

Figure 2.8: Alstom Coradia iLint design (Alstom, 2019).

There are significant developments to fuel cell rail beginning in Europe in addition to the Alstom Coradia iLint. A consortium of companies, CAF, DLR, Renfe, Toyota Motor Europe, Adif, IP, CNH2 and Faiveley Stemmann Technik, spanning Spain, Portugal, Belgium, and Germany launched a FCH2RAIL 4-year project in January 2021, with EU funding. The project aims to develop a modular fuel cell system to combine with electric propulsion, forming a hybrid train which can use OLE and unelectrified lines. The modular nature is aimed to provide different available hydrogen ranges depending on the line or type of train, so that these could be used for multiple units, locomotives, and even freight (Millikin, 2021; RT, 2020). In Poland, PESA, working with TSA, ABB and Ballard, has unveiled a hydrogen shunting locomotive capable of 24h service on one charge. The locomotive is undergoing testing for use on a private freight line, and PESA are working on passenger rail with target 2025-26 for their first passenger train (Clinnick, 2021). In Germany, Siemens are developing their own fuel cell train using Ballard fuel cells set to begin test runs in 2023 and passenger service in 2024. The development includes hydrogen produced from wind powered electrolysis for refuelling, with the 2-car model having a 600 km range and 3-car a 1000 km range (FCW, 2020; RT, 2021). Elsewhere, in Japan, East Japan Railway Company (JR East), Hitachi and Toyota Motor have teamed up to develop hydrogen-powered hybrid (fuel cell-electric) railway vehicles (RT, 2020). In the US, Stadler Rail are developing their first fuel cell train to enter into service in California in 2024 (Zasiadko, 2019).

2.3.3. Trains and Transport System Sustainability

Public transport has a substantive role to play in the move to a more sustainable transport system. In the current mix of electricity and fossil-fuelled propulsion technology, public transport produces less pollution per passenger than private transport (cars). Even in a future decarbonised system, where all road vehicles are electric, public transport will remain more efficient in energy use. This is especially pronounced in commuter travel, as at peak travel times public transport is fuller and cars generally emptier (DfT, 2019b). Improving the sustainability of transport overall can be done through two mechanisms: reducing the emissions intensity of transport technology, and reducing the amount of travel taken, for example by creating a modal shift in transport users from private vehicles to public transport, promoting active travel, and reducing trips altogether. The use of public transport and the emissions profile of this transport are two separate topics, and incentives to improve the attractiveness of public transport may be key to reducing overall transport emissions just as much as reducing the emissions profile. Passengers will opt for the most convenient mode of transport, although convenience is a subjective choice. To shift from car to public transport, the core provisions of reliability, frequency, relative journey times, and pricing are key elements of decisions. On the other hand, the shift to sustainable transport technologies is ultimately up to the service provider as, for example, passengers have little choice of what type of train they catch to complete a journey.

Public transport growth and development, which leads to a reduction in road vehicles, comes with significant social as well as environmental benefits. A modal shift towards public transport can reduce emissions, air pollution, congestion, noise, and accidents, as well as improve social connectivity and mobility, facilitate housing development, and improve access to labour markets (Birmingham Connected, 2014; Williams, 2019c). The DfT Transport Decarbonisation Plan (2021) sets out modernisation and increase in capacity for rail, as well as creation of a cohesive, integrated, public transport network with simpler and more competitively priced fares, as key to promoting modal travel shift.

Fuel cell trains can offer most of the improvements of electrified rail, namely being cheaper to run and maintain, and quieter, but with the benefit of not requiring any trackside infrastructure (Nyberg et al., 2015). This means the trains can run on the entire network, with infrastructure work focused at depot stations for refuelling. This is a significant advantage, especially where electrification may prove costly, difficult or face local opposition. The fact that fuel cell trains can offer an alternative to both diesel and electrification is a valuable aspect of possible implementation. The NR Traction Decarbonisation Strategy recommends a focus of electrification for 96% of the remaining diesel-only track, with a remaining 1,300 km of track for fuel cell rail, and 800 km for battery (300 km yet no decision), as well as fuel cell and battery filling in the interim toward 96% electrification. The Strategy appreciates that electrification may not be universally applicable or cost-effective, and there is a scope for alternatively-fuelled rail technologies. The solution to decarbonising rail and providing improvements to passenger experience lies in using the available technologies in their optimal travel conditions, to create the most effective and efficient combination of technologies for the best possible outcomes.

2.4. Summary

This chapter provided the contextual background within which the subject of this thesis, namely fuel cell rail, sits. This chapter gave an overview of railway development in Britain, starting with the historical background to development of the railway infrastructure, and a brief overview of organisational changes in the 20th Century. The structural organisation of the railways since privatisation in 1993 was explained in more detail, as the organisational framework is likely to have an impact on decision-making procedures. The Williams Review into rail organisation was introduced, along with recent developments brought on by the Covid-19 pandemic and outcomes of the Williams Review. The conventional train propulsion technologies of diesel and electric were presented, as well as an overview of fuel cell rail. Fuel cell rail is an option to work in conjunction with rail electrification and future battery technology, to form a cohesive strategy to fully decarbonise the rail network.

Reducing transport-related emissions can be done through modal shift towards less impactful methods such as public transport, and through the decarbonisation of transport technologies. Electric rail is the established technology for decarbonisation, though it necessitates significant infrastructure and associated investment to provide electricity for train propulsion. Fuel cell rail offers an alternative method for decarbonisation which does not require extensive trackside infrastructure, meaning the trains can be implemented on the existing infrastructure, with structural changes only affecting train depots. Electric and fuel cell rail can both replace diesel rail to eliminate point of use emissions, and can reduce the overall emissions depending on the sources of electricity and hydrogen. The two traction technologies offer two approaches to rail decarbonisation, with different characteristics. The issues of emissions and cost profiles, as a means to compare between the technologies, and offer a basis for decision-making, becomes relevant, and this is the subject of the next chapter.

CHAPTER 3: LITERATURE - ANALYSIS CONTEXT AND ACCOUNTING

3.1. Introduction

This chapter forms the second part of the literature review, covering the background relevant to the analytical framework. While the previous chapter reviewed the context of rail, which is the subject matter of this thesis, this chapter provides the context within which the subject of rail is analysed, to deliver a means of evaluation. There are three parts to this chapter. The first part introduces the topic of Full Cost Accounting (FCA), which places the context for decision-making based on the inclusion of internal and external costs. The second part focuses on the internal costs, that is the analysis of capital and operational costs within a Lifetime Costing framework. Finally, the third part focuses on the external costs, analysis of emissions, monetisation of the impacts of emissions, and methodologies for evaluating the external costs. These three sections build upon each other to explain the context relevant to the analysis used to compare between rail technologies, which is the subject of Chapters 5 and 6. This thesis amalgamates elements of Full Cost Accounting, namely evaluation of the internal costs over the lifetime of a train, and the monetisation of emissions impacts for inclusion into Overall Costs, to formulate a full picture of costs as applied to the British rail system. Brought together, these elements follow the aim of this thesis, that is to explore the internal and external dimensions of costs of options for rail decarbonisation. This chapter brings together a number of concepts, relevant to the understanding of the research analysis. For ease of explanation, definitions of these concepts are summarised in Table 3.1 as follows.

Table 3.1: Clarification of terms used in context of the thesis analysis.

Concept	Definition
Capital Costs	The initial costs involved in obtaining an asset.
External Costs or Externalities	The impacts caused by an entity but not paid for by the entity.
Full Cost Accounting	Integration of an entity's internal costs and external costs.
Internal Costs	The capital and operational costs directly paid for by an entity to have and operate an asset.
Lifetime Costs	The internal costs over the expected lifetime of the asset.
Operational Costs	The ongoing costs involved in owning and operating the asset.
Overall Costs	The sum of internal and external costs over the lifetime of the asset.
Sustainable Development[1]	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Full Cost Accounting (FCA), is the integration of an entity's internal costs and the external costs caused by its activities, products, systems etc. (Canadian Institute of Chartered Accountants, 1997). Although this thesis does not undertake the formal process of an entity-level FCA, an understanding of FCA provides the contextual background to explain why an analysis of internal and external costs is relevant to decision-making. FCA has been presented in the literature as a means to 'correct' market pricing in the pursuit of sustainable development. FCA is a 'potentially radical tool that could transform current economic context within which business and society operate' (Bebbington et al., 2001). The European Commission recognised the potential for FCA in sustainable development in the 'Fifth Action Programme' (European Commission, 1993), and this has been followed by calls for and attempts at standardisation of the methodology (CICA, 1997; Bebbington et al., 2001). As FCA includes both internal and external costs, it shows a broader picture

[1] This definition may involve differing interpretations, but is the core concept for sustainable development defined by the Brundtland Report (United Nations, 1987).

of the total costs surrounding a product or process and quantifies the social and environmental impacts. This can prompt debate around sustainability, and influence decision-making (Unerman et al., 2018).

Lifetime Costing is the evaluation of all relevant capital and operational (internal) costs to deliver function over the lifetime of an asset, in this case a train. In the literature, Lifetime Costing is generally termed total cost of ownership (Dumortier et al., 2014). However, because in this research the ownership and operation of assets are split between different entities, the term total cost of ownership was deemed unsuitable. Altering the term to Lifetime Costing helps to emphasise that this research is focussed on the system costs involved in providing a rail service, regardless of the entity responsible for those costs. Lifetime Costing refers solely to the internal costs of a system, those which are paid for directly in order to have and operate the item in question over its lifetime. External costs, by contrast, are the impacts created by the purchase and operation of the item, or an activity or system, but which are borne and (sometimes) paid for by a party uninvolved in creation of the impact (Bickel and Friedrich, 2005). Externalities are a product of market failure, generally leading to decision-making that does not take all relevant information into account, either by the general public or policy makers, creating welfare losses (Korzhenevych et al., 2014). Externalities are, by definition, elements without market value, creating a need for methods to quantify impacts into financial terms.

Applying FCA principles of internal and external cost analysis, to compare between rail traction options to decarbonise rail in Britain, gives a more thorough basis for decision-making. A more thorough basis means the comparison is based on the emissions associated to each train technology, and monetised impacts of these emissions, and the Lifetime Costs of running each train technology. This chapter provides insight into the relevant aspects of the literature (which draws from accounting tools - see more below), which pertain to the thesis objectives of evaluating the emissions and their impacts, and the evaluation of internal and external costs, for an appraisal of the Overall Costs of future options in the rail system. This chapter also aims to give an idea of the breadth and complexity of the issues and assessment methods for monetising impacts with no market value. First, an overview of FCA provides insight into the contextual framework within which the analysis for this research sits.

3.2. Full Cost Accounting

Accounting methods, procedures, and departments are part of the fabric of companies and entities, tracking all financial inputs and outputs. It is now understood that this traditional accounting definition only records the internal costs of the entity, when there are potentially considerable external costs caused by the entity but which remain outside of the traditional accounts and procedures (such as project evaluation, the focus of this thesis). The environment and social welfare (ie. population health and wellbeing) are two distinct areas which are affected by external impacts, and they are also causally connected. The production of exhaust emissions, for example, creates negative impacts on the environment and on human health, which invariably hits the poorest in society. This means that any attempt at a sustainable development accounting approach will de facto be both socially just and ecologically sound (Bebbington and Larrinaga, 2014). The use of the environment, as a 'free' resource, is not included in traditional financial decision-making, which has led to a drive to maximise profits to the detriment of the environment (Gray, 1992; Unerman et al., 2018). The environment, therefore, is excluded from market transactions (except insofar as market prices capture aspects of environmental costs) with externalities sitting outside of organisational decision-making. Likewise, the established means of measuring economic performance, such as Gross Domestic Product (for a country as a whole) or profits (for an organisation), also exclude environmental externalities (CICA, 1997). The following section further details environmental and social considerations in FCA.

3.2.1. Environmental and Social Accounting

Before considering environmental and social accounting, some introduction to this field is necessary. Rather confusingly 'accounting' is used by the disciplines of accounting and economics to describe similar activities that use different assumptions and involve different focuses. In essence, the scale of focus differs between the two disciplines, as does the application of techniques (critically discounting practices). Economics as a discipline captures information about an economy (of a country or of a region/settlement) to answer questions about how best to arrange the economic system to which organisations and people are subject to. Accounting, in contrast, focuses on organisations and on providing information for decision making at this level. This thesis, and the literature surveyed here, draws from the discipline of accounting to consider a range of traction technologies, the financial costs of these technologies, as well as the externalities profiles of these options. In this process, an accounting based full cost account uses economic data to convert physical externalities into monetized measurements: this is the approach used in the thesis. This framing will have important ramifications for the extent to which discounting is applied to the figures produced (see more below).

Traditional economic concepts which account only for values set by financial markets have been recognised to increase both wealth in the rich, and poverty in the poor (Bebbington et al., 2001), and have been defined as detrimental to life and planet (Gray, 1992). This has created a system which fosters development and growth, which can prove socially beneficial, but with no core accounting for the environment or welfare, can also lead to environmental and social detriment. The use of economic growth or profit accumulation as metrics for success does not allow for emphasis on environmental protection or social wellbeing. Environmental and social accounting seek to incorporate monetised impacts of economic activity into decision making and organisational performance measurement, in an effort to readdress the inequalities and injustices caused by traditional economics. This is especially important where decisions might create externalities in the future. Given the time lag that is often observed between the impact of an externality and the decision that has created the impact, ensuring externalities profiles are incorporated into current decision-making is difficult.

In particular, a problem that arises in any attempt at balancing social inequalities, is that those individuals, entities, and organisations with power to implement or prevent change, are invariably also benefitting from the imbalanced system (Bebbington et al., 2001). An FCA approach accounting for the environment and society - or parts of it, such as externality internalisation or sustainability accounting - therefore, needs to be coupled with policy and legal interventions to support better decision-making (Bebbington et al., 2001; Bebbington et al., 2006). Despite the perceived resistance, there is evidence of firms performing private internal accounts of their full costs (CICA, 1997; Bebbington, 2007; Deegan, 2016). Even in the absence of legal requirement, undertaking FCA can prove beneficial to the entity, largely to prepare for future developments in policy or improve social perception of the entity, which in turn can be an improved selling point (Bebbington et al., 2001; Unerman et al., 2018). The benefits are, for example:

- Proof of a better consideration of sustainability issues,
- Improvement of moral acceptability of the entity in society (‘social contract theory’ and ‘corporate social responsibility’[2]),
- Improvement of environmental performance due to awareness of externalities,
- Pre-empting future taxation or regulation policy (by being seen to be proactive),
- Pre-empting internalisation and avoiding/reducing externalities (‘internalising externalities continuum’), and
- Improvement of the long-term financial sustainability of the entity (by appreciating how current decisions might drive future costs).

There is a general perception that FCA gives uncomfortable and unwelcome information and conclusions about the sustainability of our current system, which firms, entities, organisations, and people would rather ignore. The issue with accounting for sustainability is that the lack of direct consequences means it can largely be ignored, so outside involvement through policy or regulation may be necessary. Furthermore, FCA is only a first step towards sustainability, as Bebbington et al. (2001) conclude, ‘once [identifying the unsustainability] is achieved, the truly hard work of doing something about the unsustainability begins’. Nonetheless, FCA offers a means and framework to evaluate and assess entities and activities, in the pursuit of sustainable development.

[2] Social contract theory refers to the idea that people live in a society through morally accepted behaviour, and corporate social responsibility is the idea of firms operating morally justly within their communities (Texas McCombs, 2021).

3.2.2. Full Cost Accounting Methods

FCA takes into account all financial inputs and outputs of an activity, system, or entity. It is a valuable tool to measure unsustainability, and can be used to subsequently build up sustainability (CICA, 1997). Sustainability, however, can prove unsolvable, and Bebbington and Larrinaga (2014) recommend an approach focused on evaluating a marker of sustainability quality, rather than attempting to 'solve' the issue. The fact that there is no final solution to sustainable development must not, however, be construed as a reason or excuse to disregard it. FCA provides the means to introduce sustainable development into traditional financial markets, following three given premises (Bebbington et al., 2001):

- There is a severe environmental crisis, with social dimensions,
- The concept of sustainable development is the right guiding principle, and
- If implemented, FCA would do more benefit than damage.

FCA has the potential to incorporate sustainability into existing financial frameworks, so that prices reflect 'true' costs. This could furthermore create a financial incentive towards reducing negative impacts (Bebbington et al., 2001). Therefore, delineating a standard definition and procedure for FCA (and standard method of accounting for externalities), would improve widespread understanding and acceptance of FCA procedures. CICA (1997) propose the following standard definition for FCA: 'from an environmental perspective, full cost accounting is the integration of an entity's internal costs (including all internal environmental costs) with the external costs relating to the impacts of the entity's activities, operations, products and/or services on the environment', and this can include society. The proposed standard procedure set out by Bebbington et al. (2001) follows a four-step approach to FCA:

- Stage 1: Define the cost objective - definition of the purpose and boundaries of the exercise;
- Stage 2: Specify the scope or limits of analysis - explicit specification of limits of the exercise, which externalities are to be measured to fit with the cost objective;
- Stage 3: Identify and measure external impact - generation of data to identify and quantify external impacts within the scope and objective;
- Stage 4: Cost external impact - detailed and complex assessment to monetise the external impacts identified.

The apparent simplicity of this four-step approach belies the complexity and quantities of data collection, and intricacy of judgement required at each stage, especially in the final monetisation step (Bebbington et al., 2001). The additional question of if, and if so how, costs might be discounted to reflect the time value of money also presents complexity in this field.

FCA, as practiced by accounting scholars, tends not to consider the time value of money: that is, it does not discount future costs and revenues or externalities profiles. This is not to say that accounting does not use discount factors in some processes: for example, in project appraisal where cash flows can be established with reasonable accuracy and where time frames are relatively short. In this case a 'net present value' might be calculated for different projects so that a rank order of projects can be established (projects are often also evaluated on how quickly the financial outlay can be paid back on a pure cash basis with no discounting). Where an accounting based FCA is seeking to model distant social and environmental costs, it does not use discounting for a number of reasons. First, if externalities are going to be experienced in a more distant future (this is the case with climate change) even modest discount rates will make future climate impacts negligible in a financial sense even though there is strong scientific evidence that climate change impacts need to be tackled as quickly as possible (this is the central message of Stern, 2006). Second, there are ethical issues in applying discount rates (for a summary of the debate, see Davidson, 2015) which pre-dispose social and environmental accounting scholars not to use them in project appraisal that is seeking to explore externalities profiles, preferring instead to see the accounting process as the start of a wider conversation within organisations (and between organisations and their stakeholders) about the relative merits of different courses of action (Bebbington et al., 2001; Bebbington and Larrinaga, 2014).

The FCA reasoning and procedure inform the underlying approach taken in the analysis of this thesis. However, a formal FCA is a detailed accounting tool undertaken within or on behalf of firms, and with access to detailed, often private, datasets - thus this thesis should not be taken as a FCA evaluation of GB rail. Such an endeavour would necessitate the cooperation of all of the entities involved in rail provision, as laid out in Chapter 2. FCA evaluates the internal and external costs to define the sustainability of a process or entity, and this approach is used to evaluate and compare the different options for rail traction. Chapter 4 describes the methodological procedure followed in this thesis, and this is informed by the four-step FCA approach outline above. The remainder of this literature chapter looks in detail at internal and external costing, and procedures for evaluation.

3.3. Lifetime and Internal Costing

The term Lifetime Costs is used in this thesis to refer to the capital and operational costs of purchasing and running a train, which are also defined as the internal costs. Lifetime Costs can be an important, though often neglected, factor in decision-making - for example, buying a car with a higher purchase price but lower running costs can be a financially beneficial investment over the lifetime of the car. However, often the capital cost of a product takes precedence over the Lifetime Costs, because capital is easier for the consumer to evaluate (Wu et al., 2015). Taking Lifetime Costs into consideration can be particularly important for sustainability measures, as often more sustainable options may have higher capital costs but lower operational costs. For example, renewable electricity production has low operational costs compared to fossil fuel and nuclear generation, which both necessitate the purchase of fuel. However, the capital costs of installing renewable generation are generally higher than that of established fossil fuel technology (although that is reducing). An evaluation of the Lifetime Costs can show what the actual costs would be over the lifetime of the energy generation facility, and determine which option is the most cost-effective.

In the literature where similar evaluations of propulsion options are taking place, studies have used Lifetime Cost analysis to compare hybrid and electric vehicles to internal combustion engine vehicles, with some studies also including fuel cell vehicles (Al-Alawi and Bradley, 2012; Wu et al., 2015; Offer et al., 2010). The findings of these studies vary, but there is agreement that the discrepancy between capital and operation costs mean hybrid and electric vehicles only become cost competitive above a given driving range threshold, and for some consumers that threshold may be unreasonably high. Jones et al. (2020) performed a lifetime cost analysis for urban heavy duty road freight, comparing diesel, battery, and fuel cell. The analysis determined that the mileage travelled was an important factor in cost competitiveness, as well as the implementation of low emissions zones to make fossil fuel freight more expensive. In the literature gauging the uptake of sustainable technologies, there is a focus on the need to reduce capital costs, but little on Lifetime Costing of technologies, and nothing could be found using a Lifetime Costing approach to evaluate rail traction.

Lifetime Costing is often overlooked in decision-making, in favour of the more immediate impact of lower capital costs (Wu et al., 2015). Long-term planning is a necessary part of lifetime costing, which can be a benefit or a drawback. Lifetime costing implies owning a battery-electric vehicle, for example, for its full lifetime - or at least until the higher capital and lower operational balance out with the alternative fossil fuelled car (Wu et al., 2015). Ownership can also be a potential issue: for example, with rental properties, the capital cost of solar panels would be paid by the owner, and the lower electricity bills paid by the renter - so the owner does not have the financial incentive Lifetime Costing can offer. The benefit of Lifetime Costing is that it can highlight potential cost savings when the lifetime use of a product is taken into account, as opposed to comparing solely on capital costs. An analysis of the Lifetime Costs associated with running rail services is put together with an analysis of the external costs from emissions impacts into the Overall Cost analysis. The next stage is to undertake an emissions analysis and impact definition through monetisation.

3.4. Emissions, Impacts and External Costing

3.4.1. Emission Factors

Air pollution emission factors are values that attempt to relate the quantity of pollutant released with an associated activity. Emission factors are generally expressed as a mass of pollutant per unit appropriate to the activity, such as mass, volume, distance or time (Environment Protection Agency, 2019). Databases of standardised factors are generally publicly available, which can be used to estimate emissions from activity data (Department for Business, Energy and Industrial Strategy, 2019a). The factors enable long-term standardisation of emissions between sources, areas, or technologies, and facilitate estimation of emissions release without the need for measurement of every process. Emission factors are however limited by the quantity and reliability of data available with which they are created. As such, they are not recommended as representative for short-term and localised emissions release estimation (EPA, 2019).

Emission factors are generally created using averaged data, representative of the activity or situation for which the factor illustrates the emissions release. The data used to create emission factors is obtained either from direct measurement of emissions or mass balance analysis (EPA, 2013). In the United Kingdom, detailed emissions factors relating quantities of pollutant released per unit of activity are available from the National Atmospheric Emissions Inventory. These emissions factors are produced using sources from the European Environment Agency, the Intergovernmental Panel on Climate Change, the United States Environmental Protection Agency, and from direct UK research for more country-specific factors (Department for Environment, Farming and Rural Affairs, 2020; National Atmospheric Emissions Inventory, 2017). BEIS produce an annually updated report on emissions factors for company reporting, which is aimed at businesses to calculate their annual emissions (BEIS, 2019a).

The Office of Rail and Road publishes an annual record of overall British rail emissions that reports the total emissions from traction energy on the British rail network, including average emission per passenger-km. This data is based on the calculated total electric and diesel energy consumed for traction, and standard CO_2e emission factors for electric and diesel energy (Charlton, 2019). The 2018-19 report stated that 3,976 million kWh of electricity, and 469 million litres of diesel, were used for rail traction in Britain, which produced 2.465 million tonnes of CO_2e, equivalent to 36.6 gCO_2e per passenger-km (Charlton, 2019). Although this record provides the emissions produced by the whole rail industry, it does not differentiate between train propulsion type. There is also the European Union Directive 2004/26/EC, which places emissions limits on trains built since 2006, which can be used as emission factors (Transport Policy, 2018). However, as has been previously mentioned, this directive does not cover all British rolling stock (ORR, 2020a). Furthermore, the Directive only covers emissions of nitrous oxides, carbon monoxide, hydrocarbons, and particulate matter, and some trains may produce less than the authorized limit. As detailed emission factors for rail do not seem readily available, there is a need to retrospectively build up emission factors, to give an accurate evaluation of emissions. This was done by Hobson and Smith (2001), who calculated emission factors based on real train running conditions for a selection of rail classes, which is detailed in Appendix 2, A2.1. These emission factors are used directly in the emissions analysis in Chapter 5. A more direct way of calculating carbon dioxide emissions is based simply on the amount of fuel used[3], however this method cannot be used for other pollutants, the emissions of which depend on the efficiency of the engine burning the fuel. Emission factors are often combined with models, such as dispersion models, to precisely define the nature and geography of impacts - this is the subject of the next section.

3.4.2. Modelling

Models are key to building an appraisal of the impacts of pollutants and emissions. Models can be used in conjunction with emission factors as above, or with monetisation methods defined below (or both), to determine the impacts caused by externalities. They are versatile, and can be developed for global or national use, or for a very specific geography, and to address any aspect of the emissions and impact evaluation.

In the externality literature, Sun et al. (2010) used the AVCEM (Advanced Vehicle Cost and Energy-Use Model) and UC Davis' SSCHISM (Steady State City Hydrogen Infrastructure System Model) to determine the societal lifetime cost for hydrogen vehicles, by modelling the vehicle costs and the hydrogen fuel costs. Yim et al. (2012) used the National Trip End Model (NTEM) for population development, and the Weather Research and Forecasting Model (WRF) to analyse health and mortality impacts from emissions from aircraft in the UK. The Market Allocation (MARKAL) model was used by Nguyen (2007) to model emissions from the Vietnam power sector, and the MESSAGE model addresses energy system planning, policy analysis and scenario development (Klaassen and Riahi, 2006).

[3] A litre of diesel combusted produces 2.62 kg of CO_2 (BEIS and DEFRA, 2019), but different engines will require different quantities of diesel to travel the same distance. Other pollutants however are products of incomplete combustion and by-reactions, and these depend upon the engine, not the volume of fuel.

Dispersion models are commonly used to define the impacts of emissions. These models can determine the dispersion of emissions release, and the interactions of emissions, to evaluate the resulting impacts. Defining the dispersion and interactions of pollutants can be especially important in the evaluation of localised emissions and impacts, such as emissions from transport. Many dispersion models and software are available, such as AERMOD, SCREEN3, RDC, and CMAQ from the literature (AlRafea et al., 2016; Yim et al., 2012). The selection of a dispersion model is based on factors such as simulation focus, breadth of parameters, ease of use, official approval, 'specialities' of the model, and the format results are given in. Models form an important part of the evaluation contained within the external cost evaluation methodologies detailed in Section 3.4.4, along with monetisation of impacts.

3.4.3. Impact Analysis and Monetisation

Monetising the impacts of emissions is a method of translating the impacts into a financial language, which is easier to include in economic markets and decision-making processes. Financial figures can also be easier to understand than emissions values. Monetisation of goods without a market value creates a system to include environmental and social considerations into market practices, and enables the presentation of impacts in a format relevant to non-specialists in external cost analysis (Krewitt, 2002; Herbohn, 2005; Gasparatos et al., 2007; Unerman et al., 2018). This monetisation, however, is not the single solution to the presence of externalities, due to the fact that there is no standardised and objective method for determining values (Cairns, 2007). This means that monetised impacts cannot necessarily be accepted as the definitive market value, as they can be based on incomplete information. The problem that arises is that this can result in a misallocation of resources, which is problematic if it is believed all impacts are taken care of, potentially leading to complacency towards reducing impacts (Lamberton, 2005; Herbohn, 2005). Monetisation is nevertheless a useful tool to redress the misallocation of resources which leads to environmental and social degradation. Monetisation of emissions is used to draw out insights into the impact of air pollution caused by rail propulsion systems. The rest of this section describes the most common methods for assigning a monetary value to non-market items, including air pollution impacts.

Willingness to Pay and Willingness to Accept

These two methods stem from the same concept but can be applied using different decision forms. Willingness to Pay (WTP) is the price an individual is willing to pay for something - generally relating to the higher price paid for a more sustainable item - or the price willing to pay to avoid a risk or danger. Willingness to Accept (WTA) is the compensation a consumer would accept to put up with something, such as noise disturbance. In emissions impact analysis Willingness to Pay is the more commonly used method. An example of WTP in use is in the housing market, where house prices are not only determined by the objective size, materials, finishings etc., but also by environmental factors surrounding the house such as presence of roads or parks - in this instance called hedonic pricing (Hargrave, 2020).

Breidert et al. (2006) detail a classification framework for determining WTP, shown in Figure 3.1. The framework shows two main method categories for WTP measurement: revealed preference, through price-response data collection, and stated preference, through survey-based data collection. The stated preference approach relies on information given by survey respondents based on theoretical choices, and often this is the only possible method for determining pricing if there is no market share for the item. The fact that the stated preference approach relies on survey responses where the responses bear no consequences, does mean the results can be based on subjective data. The revealed preference approach increases the objectivity of WTP estimates, as the data is based on market pricing data and purchasing behaviour, though this data may not always be available. Selecting the method for measuring WTP may also depend upon constraints such as time and money. Within the stated preference branch, indirect surveys are the most popular, where the customer states preference on whether the item is worth a given proposed price. For direct surveys on the other hand, the customer must give their own value of a product, which can lead to collected data with significant deviations from the average value (Breidert et al., 2006). The revealed market data preference method follows current market values most closely, which can lead to the conclusion that this is the most reliable method. However, in the situation where market values do not appropriately reflect the social and environmental impacts of an activity, stated preference methods can provide more valuable insights to estimate externality costs. Where possible, it is important to select the most suited and accurate WTP methodology for the given application, and to be aware of sources of uncertainty in the results.

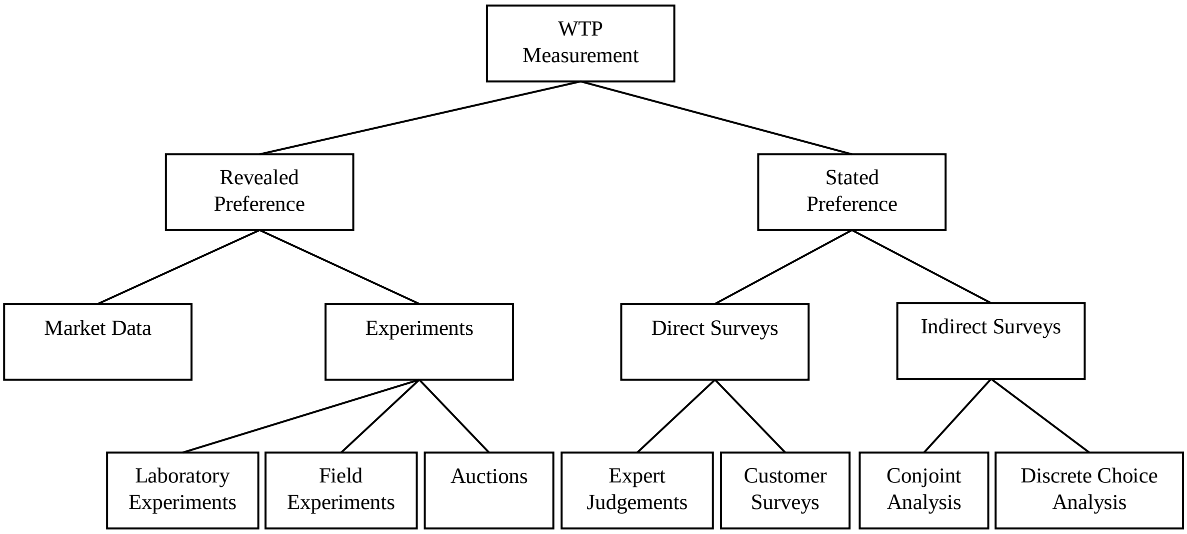

Figure 3.1: Framework of Willingness to Pay methods (reproduced from Breidert et al., 2006).

Stobierski (2020), on the other hand, assembles the methods for obtaining WTP into four categories, with less emphasis on the opposition of revealed and stated preference, which can be applied within the four categories:

- Surveys and focus groups: asking customers' WTP for the product or service.
- Conjoint analysis: type of survey involving ranking of different bundled features. Discrete choice analysis is similar, but involves discrete, separable features which can become revealed as related within the analysis.
- Auctions: revealing customers' WTP through potential to obtain the product or service.
- Experiments and revealed preference: use of data about customers' past choices.

Research into how socio-economic factors (such as wages, experience, education etc.) affect WTP and WTA preferences, indicates that rather than being point estimates, valuations should be treated as ranges of possible values. It has also been shown that survey respondents may intentionally state a higher or lower WTP to, for example, keep prices low or to appear more ethical (Breidert et al., 2006).

Southall and Khare (2016) studied the feasibility of hydrogen for transport produced from localised renewable energy sources and used WTP to evaluate motorists' attitude to paying for a cleaner fuel. They found a discrepancy in the respondent's stated concern for the environment but unwillingness to take a financial penalty for a more expensive, clean fuel. This discrepancy shows that while WTP can provide meaningful insight into preferences and infer values from stated preference, there may be a difference between stated and revealed values. Zhao et al. (2017) used their own choice experiments to measure WTP in order to evaluate the environmental cost of coal-fired power in China, and their findings showed that respondents' chief concerns were green development and pollution reduction. WTP and WTA are key tools for attributing market prices where none exist, based on stated or revealed individual preferences. The monetisation method described in this section relies on respondent choice to determine values, while the next method contains more objectivity, and makes use of market data where possible.

Cost of Illness and Burden of Disease

Cost of Illness (COI) and Burden of Disease (BOD) monetise the societal burdens of illness or disease. These methods aim to cover all aspects of illness and disease, including medical and medicine costs, equipment costs, loss of income and work hours, carer costs, and ensuing health costs (such as impacts to mental health). COI and BOD estimations describe the economic burden of illness to society, and are most commonly used by the World Health Organisation. Air pollution can cause significant negative health impacts, and the costs (both monetary and social) are typically borne by the sufferers and healthcare system (Newton, 2015). The COI/BOD procedure can be used to monetise the health impacts of air pollution.

The methods for estimating COI/BOD can be organised in three categories based on the type of data used, and within each category there is a choice of two approaches. The first category of data is epidemiological data, that is data directly related to the nature of illness or disease, and this can be collected using prevalence (over all cases in a defined timeframe) or incidence approaches (only new cases). The second category of data is economic costing methods, and these can follow a top-down (starting from the total value and defining categories) or bottom-up approach (starting from data sets and calculating for each category defined). The third category of data refers to the time between the project initiation and data collection, in which case studies can be defined as retrospective (after the event) or prospective (during the event) (Tarricone, 2005).

COI and BOD estimates consist of direct healthcare costs, direct non-healthcare costs, and indirect costs. The resulting value can be classed as an opportunity cost, that is a benefit which could be enjoyed if there was no illness or disease (Tarricone, 2005). The direct costs cover all aspects of treating the illness, from medicine and hospitalisation costs through to training and life support (including mental health and suffering impacts). Direct non-healthcare costs include aspects such as legal costs, childcare, additional elements which are necessitated by the presence of illness. Indirect costs include elements such as loss of productivity, job loss, and loss of leisure time, which can compound negative impacts (Jo, 2014). Some direct costs can be evaluated using market prices, such as medicines, however many costs are services where the market prices do not reflect value. Productivity costs, for example, can be estimated using wages, though these are not necessarily an adequate measure of output, and ignore unpaid work). Furthermore, the costs of informal (unpaid) care includes loss of wages, and intangible effects such as loss of leisure time and fatigue (Tarricone, 2005).

COI and BOD studies aim to be descriptive of the costs caused by an illness or disease, giving objective results. These results can however be subject to interpretation, which can create detrimental impacts. For example, an illness could be identified as having a high cost to society, and is subsequently prioritised for research funding, whilst another illness which could be easily remedied remains untreated due to it being given a low priority with a low cost to society (Byford et al., 2000). Whether data is produced from objective or subjective resources, this demonstrates the role of interpretation. These monetisation methods are used in the calculation of external costs.

3.4.4. Methodologies for External Cost Analysis

External costs, or externalities, are defined as the impacts created by the purchase and operation of an item, activity, or system, but which are borne and paid for by a party uninvolved in creation of the impact (Bickel and Friedrich, 2005). Externalities are a product of market failure, which arise when there are no internal consequences to an instigated impact, such as a cost or regulation, caused by the use of incomplete information (Unerman et al., 2018). The concept of an activity potentially creating a negative social impact was first introduced by Pigou in 1920, in his publication '*The Economics of Welfare*'. Pigou also touched on the idea of internalising these impacts through tax. In 1988, Hohmeyer published an evaluation of the externalities of the energy system in the Federal Republic of Germany, showing that renewable energy, while incurring higher direct costs, had less external costs associated with it. Therefore if the internal and external costs were taken into account, a different view could be formed as to the overall cost profiles associated with different energy production technologies. Hohmeyer (1988) found that the non-inclusion of external costs lead to a misallocation of resources causing costs to society, and specified that it is government responsibility to introduce policies to internalise external costs. External cost analysis featured in political decision-making in the 1990s and early 2000s with the introduction of the UK's Climate Change Levy in 2001 (UK Government, 2021). Externality costing is seeing a political resurgence, particularly in the context of biodiversity loss. The most recent report of the Dasgupta Review (2021) into the economics of biodiversity recognises the need for cost accounting and valuation of the environment to work in favour of nature. As with FCA methods, there is no standard method for calculating external costs. The rest of this section explores seven methodologies for evaluating external costs in the areas of energy, transport, and product development. The methodologies chosen are a mixture of those most relevant to the topic of rail, and some chosen to demonstrate the breadth of areas in which external costing analysis can be applied.

ExternE

The 'External Costs of Energy' (ExternE) methodology provides a framework for expressing externality impacts in monetary terms, and aims to cover all external impacts relevant to health and environmental degradation. The programme was developed from a series of projects undertaken between 1991 and 2005, as part of a collaboration between the European Union and the United States Department of Energy. Initially the project focused on the evaluation of environmental and health damage costs from electricity production. Since then the methodology has been expanded to evaluate electricity, heat, and transport. This technical work aimed to create consistently derived external costing factors for use in policy making (Bickel and Friedrich, 2005).

ExternE developed a new method of evaluating damages: the Impact Pathway Approach (IPA), which is described as a separate methodology below, as it is often used independently of the ExternE project. ExternE uses WTP, market pricing, and policy valuation to monetise impacts of pollution, and justifies impact monetisation as means to improve market efficiency for societal benefit. The ExternE methodology covers three impact categories for direct and indirect effects, each of which is treated separately and with different recommended methodologies:

- Environmental impacts (caused by a substance or energy release into the environment, including air, soil and water): IPA,
- Global warming impacts: damage quantification and avoidance cost approach, and
- Accidents (impacts to the public and occupational accidents): damage costs and probability estimates.

Impacts on health are the highest damages estimated within ExternE, and there is particular attention paid to the role of air pollution. The ExternE guidance cautions about the high uncertainties, but also reports that 'even an uncertainty by a factor of three is better than infinite uncertainty' [by ignoring the costs] (Bickel and Friedrich, 2005). The ExternE assessment has been integrated into a publicly available online model, the EcoSenseLE model, an integrated atmospheric dispersion and exposure assessment. The model analyses air, water and soil pollution, evaluating physical impacts through exposure-response functions for human exposure to harmful pollutants, and monetises these physical impacts, for a defined scenario, using data and procedures developed in ExternE (Institute of Energy Economics and Rational Energy Use IER, 2017).

Impact Pathway Approach

The Impact Pathway Approach or Assessment (IPA) is a methodology to evaluate and quantify environmental costs and benefits, and express them in monetary terms. The IPA method aims to collect and evaluate all the external impacts from pollution released and present economic valuations for the impacts (Bickel & Friedrich, 2005). The method builds up an external cost profile for a given activity, assessing source emissions through to the physical impacts and costs of these emissions, following four steps:

- Emission: source and pollutant specification,
- Dispersion: pollutant concentration change calculation,
- Impact: evaluation of pollutant exposure and resulting damages, and
- Cost: economic valuation of the impacts.

Pollutants can have direct and indirect effects (through the food and water chain), and can also chemically react to form different products, such as sulphates produced from an initial SO_2 release (Bickel & Friedrich, 2005). Thus, although the basic IPA method is designed to be simple, the evaluation required within each step can be scientifically complex. ExternE and the IPA were developed to evaluate the absolute external costs of a specific activity, which comes with inherent uncertainty. The following method bypasses this issue by focusing the evaluation on *changes* to air quality, creating comparisons between activities but not the estimation of absolute external costs.

Air Quality Benefits Assessment Tool

The Air Quality Benefits Assessment Tool (AQBAT) was developed by Health Canada, part of the Canadian Government, in 2011. The aim of the programme was to evaluate health impacts specifically from changes to the local air quality, generally brought about by pollution.

The methodology presents an accumulation of data inventories in combination with concentration-response functions, WTP, and both COI and BOD methodologies to determine air quality changes and the impact on health. The product is a computer application created to demonstrate the effects regulation changes would have on air quality and health, and as such is designed to be simple to use for a wide political audience (Government of Canada, 2017). The AQBAT model includes a monetisation of health effects caused by changes in the ambient air quality, and aims to improve awareness and education around externality effects on society.

The AQBAT uses Microsoft Excel, and allows the user to input known quantities and retrieve data for a specific scenario. The model file uses population data, pollution concentration data, baseline health rates, concentration-response functions and health endpoint valuations. This relies on inventories of data, such as emissions inventories, which come from a mixture of monitoring measurements, sampling, and estimation. The monetisation of health effects partly follows a WTP method, with more detail provided by COI and BOD estimates, including direct costs such as medical expenses, and indirect costs such as loss in work hours (Barn et al., 2011).

The AQBAT includes data collected from direct measurements, but it is still subject to the uncertainties prevalent in external cost estimation methods. The methodology is largely specific to Canada, but can be applied in other countries, bearing in mind climactic differences (Barn et al., 2011). The following method was also developed in Canada, but with a focus on transport emissions.

Transportation Cost and Benefits Analysis

The Transportation Cost and Benefit Analysis (TCBA) programme was initiated in 2009 by the Victoria Transport Policy Institute (VTPI), an independent research institute based in Canada. The aim of the study was to enable full impact analysis of the transport system, considering both the benefits and impacts. The full study, including guidance on how to apply the information and a spreadsheet for undertaking the cost analysis, are all readily available online. The aim is to make the information and methodology easily accessible and usable for policy analysis and community planning. TCBA includes 11 modes of transport, and highlights that the idea that 'improving' transport generally equates to increasing transport, and this ideology can create social externalities. The TCBA method emphasises how transport can negatively impact communities, and that there is a need for better knowledge and planning to reduce inequalities resulting from this social impact. The study focuses on the social externalities of transport, aiming to work towards removing the market distortions, inefficiencies, and inequalities arising from transport infrastructure (Litman and Doherty, 2009).

This methodology is a societal cost-benefit analysis of transport uses, and evaluates 23 costs associated with transport, including land value, air pollution, greenhouse gas pollution, resource externalities, land use impacts, water pollution, and waste. The TCBA methodology uses a substantial inventory of data collected from other sources, such as ExternE, and using methods such as damage costing and WTP, for its economic evaluation and determination of internal and external costs. There is also evaluation of some monetisation methods, such as damage cost, revealed preference, stated preference, prevention cost, compensation rate, travel cost, WTP, and WTA (Litman and Doherty, 2011).

The TCBA report is a collation of data into a format which allows greater accessibility to the information. There are thus the usual uncertainties with the data, though this is decreased by the array of data collection sources used. TCBA also includes analysis of the external benefits of transportation, which can often be disregarded in external cost evaluations (Litman and Doherty, 2011). The following method is also focused on transport externalities, but developed in Europe.

Handbook on External Costs of Transport

The Internalisation Measures and Policies for All external Cost of Transport (IMPACT) study was commissioned by the European Commission due to an amendment of Directive 1999/62/EC, that levied charges on heavy duty vehicles for defined infrastructure use. Its aim was to summarise existing knowledge on externality costs in the transport sector, and provide a model for assessing external costs, for use with policy development. The study led to production of the Handbook on Estimation of External Costs in the Transport Sector in 2008 (Maibach et al., 2008), which was updated in 2014 and renamed the Handbook on External Costs of Transport (HECT) (Korzhenevych et al., 2014).

The HECT focuses on all forms of transport, using data from an extensive literature review of EU studies which use methods such at IPA, WTP and WTA, to give a broad summary of external costs from transport in Europe. The study makes recommendations about calculation methods, input data, and gives some default scenario values (Maibach et al., 2008). The 2014 update expanded the external cost parameters covered, so that the HECT evaluates the following parameters and recommends monetisation methods for each parameter (Korzhenevych et al., 2014):

- Congestion: speed-flow relations, value of time and demand elasticities,
- Accidents: risk elasticity using values of statistical life based on WTP or WTA,
- Noise: impact pathway approach with WTP (health) or WTP (annoyance),
- Air pollution: impact pathway approach using values of statistical life based on WTP or WTA,
- Climate change: avoidance cost or damage cost approaches[4],
- Environmental impacts: compensation cost approach, and
- Infrastructure scarcity: using WTP, WTA.

According to the HECT, road transport causes the highest externalities of all transport modes, and this is also the highest researched area. The Handbook provides three levels of available analysis: the first level of analysis is the most detailed, and calculates the external costs based on the specific values from emission models provided by the entity undertaking the evaluation. The second level of analysis is less detailed but does not require detailed emission models, instead calculating external costs based on the Handbook's own values, modified to fit a specified situation. The third level of analysis is a 'rough and ready' estimation using country-wide averaged results for a rapid and qualitative analysis (Korzhenevych et al., 2014). HECT is an extensive study of transport externalities, covering all transport modes, seven categories of impacts, and reviewing EU-wide literature. The following two methods are very different in that they evaluate

[4] Avoidance (or abatement) costs are the costs associated with alternative consumption or production processes which enable the prevention of environmental deterioration. Damage costs are the costs incurred from the effects of environmental degradation (Organisation for Economic Co-operation and Development, 2005).

external costs through the monetisation of Life Cycle Assessment, but they have been included to show the versatility of external cost monetisation.

Stepwise 2006

Stepwise 2006 was developed by Bo Weidema, with EU funding, between 2005 and 2006. The aim in development was to produce a simple method of determining the environmental burden of products and hence encourage the uptake of comparatively greener products. Stepwise 2006 uses Life Cycle Assessment (LCA)[5] to determine environmental burdens, which are then converted to financial terms or Quality Adjusted Life Years (QALYs). The methodology is used to produce initial (simplified) Environmental Product Declarations (EPD) for small-medium enterprises based on the ISO 14025 standard (Zackrisson et al., 2008).

Stepwise provides a cost-effective and more accessible methodology to undertake an initial simplified EPD. There are six steps in the methodology:

- Scoping - selecting product focus,
- Inventory - data collection,
- LCA calculations,
- LCA examination and formulate EPD,
- Review of EPD, and
- Plan for next step to a 'real' EPD.

[5] Life Cycle Assessment (or Analysis) is a methodology used to evaluate the environmental impact of a product throughout its lifecycle, considering resource use, human health, and ecological detriment (International Organisation for Standardisation, 2006).

As this is based on an LCA, the full product life-cycle impacts are included. To simplify the process, the Stepwise model uses generic data at all stages, except where site-specificity is required. The result allows identification of areas where the environmental performance can be improved (Zackrisson et al., 2008). The Stepwise methodology has been developed using monetisation values from ExternE (Weidema, 2014). The focus of this methodology is on physical products and their environmental burden, which shows how the same parts of external costing methods can be used in different applications.

Environmental Priority Strategies 2000

Environmental Priority Strategies (EPS) 2000 is the updated methodology from an initial collaboration between Volvo, the Swedish Environmental Research Institute, and the Swedish Federation of Industries in 1989. The 2000 updated method was developed in the Centre for the Environmental Assessment of Products and Material Systems (CPM), funded by the Swedish National Board for Technical and Industrial Development, and jointly researched between Chalmers University of Technology in Sweden, Volvo, and other industries (Steen, 1999).

EPS is similar to Stepwise 2006: the methodology uses LCA to determine impacts and monetises these using WTP, and aims to demonstrate the environmental impact of a product. EPS prioritises the most important and relevant elements of the analysis, in combination with a simplified LCA, and WTP monetisation. This simplification leads to a high degree of uncertainty, which the methodology also quantifies. It is generally intended as a simple and economical method for companies to internally compare their own production options. For example during product development, it can be used to drive the selection of a production process, based on environmental sustainability. EPS also enables an entity to demonstrate growth opportunities in its environmental strategy (Steen, 1999). As with Stepwise, the focus of this methodology is less relevant to this thesis, but it shows a different application of familiar evaluation tools. The seven methodologies which have been reviewed are summarised in Table 3.2, and in addition this table includes the EcoSenseLE model, as a subsequent methodology to ExternE.

Table 3.2: Summary of external cost analysis methodologies.

Methodology	Source of Emissions	Impacts Evaluated	Monetisation Methods	Reference
ExternE	Energy production	Health and environment	WTP, market pricing	Bickel and Friedrich, 2005
EcoSenseLE (from ExternE)	Any source of emissions	Health and environment	WTP, market pricing	IER, 2017
Impact Pathway Approach	Any source of emissions	Environment	WTP, market pricing	Bickel and Friedrich, 2005
Air Quality Benefits Assessment Tool	Any source of emissions	Local air quality and health	WTP, COI and BOD	Government of Canada, 2017
Transportation Cost and Benefits Analysis	Transport	Social	Damage costing, WTP, WTA	Litman and Doherty, 2011
Handbook on External Costs of Transport	Transport	Heath and environment	WTP, WTA	Korzhenevych et al., 2014
Stepwise 2006	Products and processes	Environment	WTP	Weidema, 2014
Environmental Priority Strategies 2000	Products and processes	Environment	WTP	Steen, 1999

3.5. Summary

This chapter presented the second layer of the literature review, namely the contextual background to the analysis which this thesis applies to British rail. The concept of Full Cost Accounting was first introduced, as this provides the context out of which the analytical procedure used in this analysis is developed. FCA is the integration of an entity's internal and external costs, which are the costs this thesis uses to compare between options for rail decarbonisation. The following section described the analysis of internal costs, and emphasised the importance of estimating costs over the lifetime of an asset. The final section explored external cost evaluation, in the order of procedures to follow to define external costs. The first level is to analyse the emissions, and this chapter presented emission factors as the means to accomplish that for rail. The second level uses modelling to determine the extent, location, and nature of impacts. The third level is monetisation of the impacts caused. Finally, this chapter outlined a selection of external cost analysis methodologies, which bring together these levels of analysis.

Lifetime costing accounts for all financial costs involved in the acquisition and operation of an asset, and provides a more informed basis for decision-making than a comparison of purchase costs alone. This thesis combines Lifetime Costs with external costs into the Overall Costs, in consideration of the research aim of exploring the internal and external dimensions of cost for British rail. External cost analysis provides a means to include more relevant dimensions into decision-making, especially when these are not captured by traditional accounting methods. Basing the analysis of rail traction options on a comparison which includes an appraisal of Lifetime Costs and monetised external impacts, develops a more sound basis for decision-making. This chapter presented a review of the literature context to the analytical methodology, which the thesis uses to compare rail traction options for decarbonisation. The next chapter uses the established context to develop the methodological procedure that is used to consider the research aim and objectives.

CHAPTER 4: METHODOLOGY

4.1. Introduction

The methodological procedure followed in this analysis is inspired by the four-step Full Cost Accounting approach proposed by Bebbington et al. (2001), outlined in the previous chapter in Section 3.2.2. The first step of defining the cost objective has been set in the aim of this thesis, that is to explore the internal and external dimensions of cost for rail technologies in Britain. The second step, to specify the scope of analysis, relates to the research objective of defining relevant case studies for examination, which is the subject of the first part of this chapter. The third step is to identify and measure external impact - this is the research objective of calculating the emissions from rail for the selected case studies, and for the three rail traction options considered (namely diesel, electric and fuel cell). The final FCA approach step is to monetise the identified external impacts, which for this thesis is the objective of monetising the impacts from rail emissions. In addition, the analysis addresses the objectives of evaluating the internal costs, and examining the Overall Costs, which combine external and internal costs.

Table 4.1 reiterates the research objectives for the analysis, and these are numbered to show where each is considered in Figure 4.1, which shows a diagrammatic representation of the methodological procedure. The structure of this chapter also follows the diagram from top to bottom. The first part of this chapter defines the case studies and the parameters within which the internal and external costs are explored. The second part of this chapter focuses on the secondary data collection, reviewing and critically evaluating the sources of data, which were used in order to address the research objectives. The second and third objectives of Table 4.1 are the subject of the next part of this chapter. The evaluation and monetisation of rail emissions are addressed in tandem, as the analysis of impacts caused by rail traction. The final part of this chapter describes the procedure followed to calculate the internal costs and Overall Costs, completing the methodology followed to address the objectives and examine the internal and external dimensions of cost for British rail. There is a final defined objective, examination of the implications for rail decarbonisation, and this is the subject of Chapter 7, following the analysis results.

Table 4.1: The thesis research analysis objectives.

Number	Research objective
1	Selection of specific and representative case studies for examination.
2	Evaluation of emissions from rail.
3	Evaluation of emissions impacts through external cost analysis.
4	Evaluation of internal costs - capital and operational.
5	Examination of the Overall Costs.

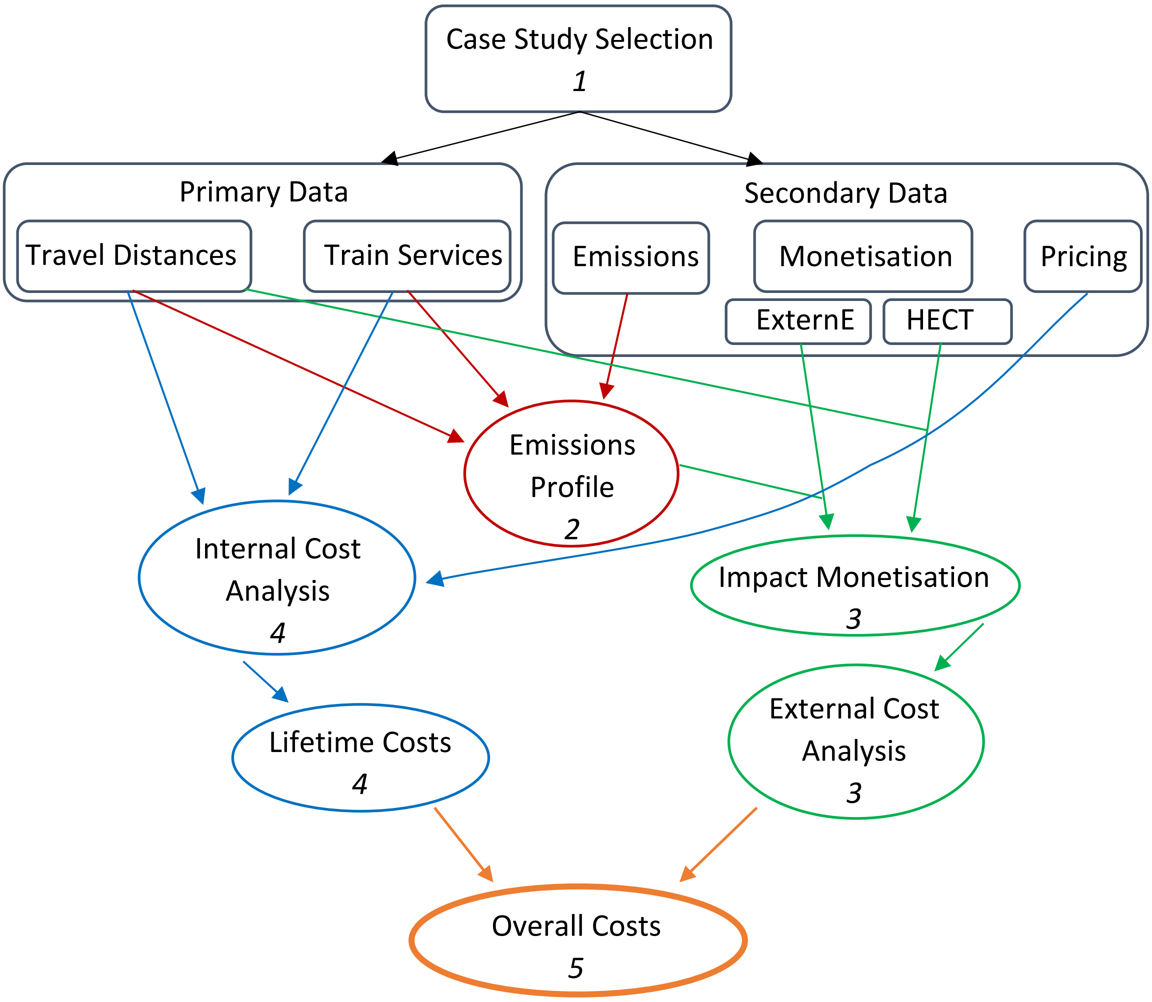

Figure 4.1: Diagram overview of the analysis methodology.

The case studies are selected to explore the internal and external costing in a range of service provision and geographical features of the British rail network. As was laid out in the research focus in Chapter 1, the case studies are centred on the city of Birmingham. This focal point was selected due to it being the largest rail hub outside of London, and featuring a mixture of diesel and electric rail similar to that of the British network as a whole (Hickman et al., 2017). The internal and external costs of diesel, electric, and fuel cell rail are explored for the rail provision of the defined case studies. For each case study, the total traction emissions for providing the service are assessed, and the emissions are monetised using external costing methodologies. The emissions and monetisation analysis forms the subject of Chapter 5. The internal costs for purchasing and operating diesel, electric, and fuel cell rolling stock for each case study are also calculated, and this is the subject of Chapter 6. The overarching assumptions and boundaries of the analysis are presented briefly, before the next section delves into the selection of appropriate case studies for examination.

4.1.1. Assumptions, Boundaries, and Basis

The snapshot year for this analysis is 2020, but using data collected pre-COVID 19 pandemic (see section 4.2.5). This research evaluates the costs and emissions of the provision of rail as a service, in order to compare between traction options for decarbonisation. The focus therefore is on the costs involved in running the railways from a technological perspective, and on the emissions produced when providing the service of running the trains. This boundary isolates rail from the wider transport system, enabling a direct like for like comparison of traction technologies, focusing only on the costs and emissions directly related to the form of traction technology. In practice, rail is not an isolated system, and changes made to reduce rail emissions could lead to more changes within the transport system, such as increased demand after electrification (sparks effect). The basis for analysis of ongoing elements such as the emissions and operational costs is the train-distance travelled, (marked train-km throughout this thesis). Travel distances are calculated for one year, and then scaled up to a 30-year lifetime basis, which is the expected lifetime of a train. The analysis and monetisation of emissions examines the upstream and downstream emissions of the transport fuel (well to wheel analysis). Upstream accounts for emissions released from fuel and electricity production, and downstream emissions are those produced when the fuel is used (i.e. train operation). As

2/3 of rail emissions are from traction (NR, 2020), this boundary includes the highest source of emissions, but excludes other sources such as emissions associated with the production and installation of infrastructure and facilities to provide energy for rail traction. Furthermore, particulate matter emissions can be produced from mechanical wear, particularly when braking, suspension from train movements, and sparking of electric components (Cha et al., 2017). This is common across all traction types and so cannot be fully eliminated, but reduces with lighter trains.

The internal cost analysis only includes relevant elements which are dependent on the train propulsion options being explored. FCA seeks to understand hypothetical cost profiles, considering the future environmental impacts of decisions, and using raw data to evaluate the issues relevant to different options. Hence the use of a 'snapshot year' on which the analysis is based, and the exclusion of time value of money - if this were included, the value of environmental impacts would not be relevant to decision-making, as discussed in Section 3.2. The following is a list of general assumptions for this research:

- Trains remain at the same level of service provision for the 30-year lifetime.
- Trains do not travel significant distances outside of the timetabled services.
- Traction is the greatest source of rail emissions.
- Operational costs remain the same for the 30-year lifetime.

4.2. Case Study Selection and Travel Distances

Three rail routes are selected as case studies for detailed examination of the internal and external costs, as a representative sample of the variety of service types that are present on the British rail network. The case studies are defined as a regional route, meaning a short-distance route with regular stops and services provided at regular intervals, a long-distance route, meaning a lengthy route which is generally undertaken by higher-speed trains and with few stops, and a rural route, meaning a mid-distance route with low passenger numbers, and low levels of service provision. The case study routes are all non-electrified services, as it is assumed that removing electrification would not be an environmentally beneficial activity, when there is still 62% of diesel-only track in Britain (Goddard, 2018).

Birmingham city is central to all three case studies, providing a point of cohesion between three separate routes. As a first step to consider the impact of rail, the emissions from rail traction within the city of Birmingham are calculated and monetised. This examination is separate to the cost comparison of rail traction within the case studies, and aims to provide context to the emissions evaluation. Assessing the emissions from rail within Birmingham illustrates the contribution of rail towards urban air pollution, and the resulting impacts to health and wellbeing. This serves to show that although rail emissions are low compared to other forms of transport, they still have a negative impact that needs to be addressed through decarbonisation. New Street is the main rail station within Birmingham, and it is the busiest station in the United Kingdom outside of London. All but one of the rail lines which pass through Birmingham stop at New Street station, and while it is electrified, 42% of services at the station are provided by diesel trains (Hickman et al., 2017). The line which does not pass through New Street passes through Moor Street station, which is not electrified, and serves more local and regional stations.

4.2.1. Birmingham City

Birmingham is the UK's second largest city, with a population of 1.14 million (2018 data, Birmingham City Council, 2021). Birmingham often refers to the wider Birmingham or even West Midlands area, but this evaluation is focused just on the Birmingham City Council area, as shown on the map in Figure 4.2. Birmingham is the UK's largest transport hub outside of London. Since 2014, the Birmingham Mobility Action Plan has set out ambitious public transport plans for the city and region, which included the introduction of a 'clean air zone' for vehicles, open in 2021, and reopening of some rail lines (Birmingham Connected, 2014). Birmingham New Street, the city's main train station, is partially underground, which has led to concerns over pollution levels. A study by Hickman et al. in 2017 found that within the station, localised concentrations of NO_2, $PM_{2.5}$ and PM_{10} regularly exceeded European Union regulation limits. They also found that the average maximum concentration of NO_2 was 1,048 $\mu g/m^3$, almost fourteen times higher than the 75 $\mu g/m^3$ average on the Birmingham Ring Road (Hickman et al., 2017). This shows that there is concern over rail emissions, and there is an opportunity to reduce these by reducing the volume of diesel-powered rail.

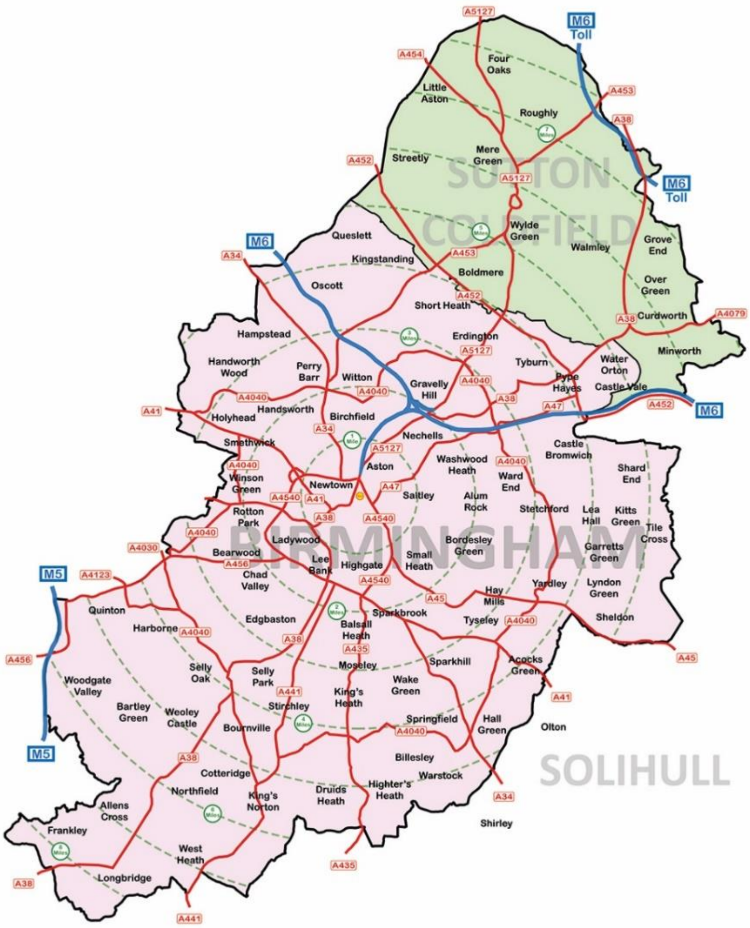

Figure 4.2: Birmingham area map (Aston SU, 2021).

Birmingham represents the British rail network, due to its traction power mix, and the variety of types of route that pass through. Services in Birmingham vary from regular, 10-minute interval, local trains, to every 2 hours or less across-country services. Services departing Birmingham reach parts of the entire network in England, Wales and up to Scotland. The variety of services passing through Birmingham also means there is a wide variety of types of train, including Diesel Multiple Unit (DMU), Electric Multiple Unit (EMU), Diesel-Electric Multiple Unit (DEMU) and Electric High-Speed (EHS). The examination of emissions impact includes all diesel and electric rail within the city limits as defined in Figure 4.3, using train distance travelled as basis. Table 4.2 presents detail of the routes within Birmingham city centre, including train type, class and carriage sets, the section and length of route these trains run on, and the approximate number of services in both directions daily. This information is used to undertake a detailed examination of rail emissions based on the specific trains and distances travelled within the city limits.

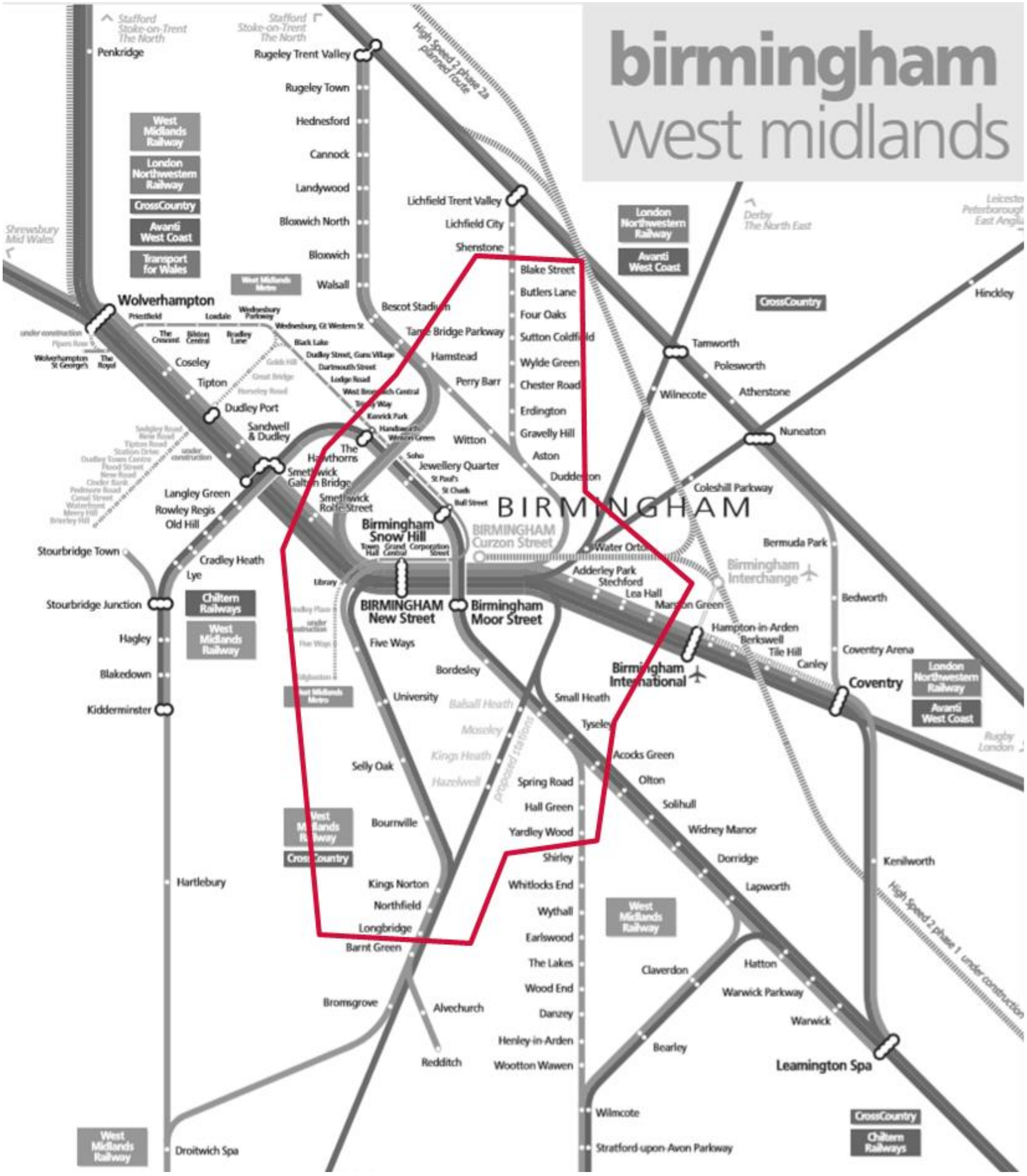

Figure 4.3: Birmingham limits rail map (Smithers, 2019).

Table 4.2: Birmingham city-centre case study services and provision.

Route (to)	Train Types	Train Classes (number of carriages)	Route Length (km)	Daily Services (weekdays)
From Birmingham New Street				
Blake Street	EMU	323 (3/6)	8.5	180
Longbridge	EMU DMU	323 (3/6) 170 (2/3/4/5), 220/221 (4), 253/254 (7), 150 (2)+153 (1)	7	340
Marston Green	EHS, EMU DEMU, DMU	390 (9), 350 (4) 220/221 (4), 158 (2/4)	5	300
Water Orton	DEMU, DMU	220/221 (4), 170 (2/3)	5.5	195
Acocks Green	DEMU	220/221 (4/5)	3.8	32
Rolfe Street	EHS, EMU DEMU, DMU	390 (9), 350 (4) 220/221 (4/5), 170 (2), 158 (2/4)	2	322
Hamstead	EMU DMU	350 (4) 170 (2/3/4/5) 153 (1)	4.8	120
From Birmingham Moor Street				
Yardley Wood	DMU	159 (3/4)	5	108
Acocks Green	DMU	159 (3/4/5/6), 168 (2/3/4/5/6), 170 (6)	3.5	150
The Hawthorns	DMU	159 (3/4/5/6), 168 (3/5), 170 (6)	3	198

4.2.2. Regional Case Study

The route chosen for regional case study is the line between Worcester Foregate Street and Stratford-upon-Avon. The route passes through Birmingham Moor Street, and is currently operated by West Midlands Trains. It was chosen as representative of the regional route type due to its very low electrification status, route length, and both train and station regularity. This route was also identified as an ideal pilot project by Kent (2020), due to its proximity to the Tyseley hydrogen hub. The case study features a large number of different services terminating between stations along the route at different times of day, and Moor Street is generally an intermediate rather than terminal station. Table 4.3 shows the stations at which services coming out from Moor Street terminate, along with the approximate midweek train departure frequency. On average, this means six trains per hour depart from Moor Street in each direction.

Table 4.3: Regional case study service provision.

Towards Worcester Foregate Street			Towards Stratford-upon-Avon		
Route	Length (km)	Service	Route	Length (km)	Service
Great Malvern (beyond Worcester)	75	irr	Stratford-upon-Avon via Whitlocks End	47	1 tph
Worcester Foregate Street	62	1 tph	Stratford-upon-Avon via Dorridge	44	1 tph
Worcester Shrub Hill	62	1 tph	Whitlocks End	14	2 tph
Kidderminster	34	2 tph	Dorridge	18	2 tph
Stourbridge Junction	22	2 tph			
Snow Hill	0.8	irr			

tph: train per hour. irr: irregular service, often extended or shortened from the usual destination early or late in the day.

The full length of this route is about 110 km, and generally all stations along the route are stopped at. The greatest reason for rail travel in Britain is commuting, with a 55% share of all journeys (Williams, 2019b), and commuting is a prevalent reason for travel on this particular route. Many of the commuter lines into Birmingham have been electrified, though a significant amount still run on diesel. This route was chosen as an example of a diesel-powered regional route that is important for regular traffic around the city. This line would benefit from the improved journey times and increased capacity offered by electric trains, but electrification would need to negotiate the fact that Moor Street is centrally located within Birmingham and parts of the tracks are underground to pass under the city. There may not be enough space for the infrastructure, and disruption to services could irrevocably damage service use, so there are potential benefits beyond cost that fuel cell rail can provide. The route is highlighted in light blue in Figure 4.4 below, along with the main terminal stations.

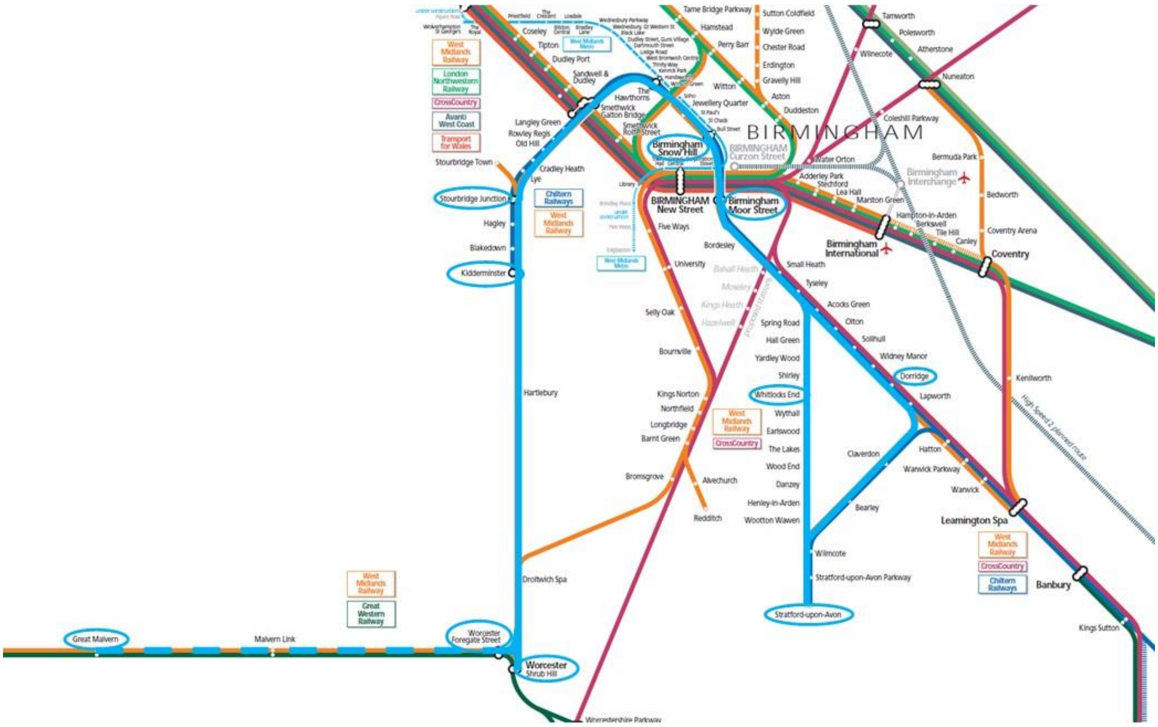

Figure 4.4: Regional route map (Smithers, 2019).

The trains operated on this route are class 172/2 and 172/3 DMU trains, constructed between 2010 and 2011 (Goddard, 2018), though for the analysis, data for class 165 trains is used as this was the closest available data. The differences between these two rail classes means the 165 data may be higher than accurate 172 data: both trains run 6-cylindre turbo-diesel engines, the 172 being 13 L, and 165 14 L, and both are of similar dimensions, but the 165 top speed is 75 mph whereas 172 is 100 mph, and the 172 is significantly lighter at 42 t versus 74 t (Angel Trains Ltd, 2019). The extra speed and power of the 172 would be expected to produce more emissions, whereas the decrease in weight and improved efficiency would be expected to reduce emissions comparative to the 165, however it cannot be accurately confirmed whether these cancel each other. In the comparison of traction technology options, the replacement electric train is based on data for a class 350 EMU, and the replacement fuel cell train is based on data for the iLint fuel cell train. Table 4.4 summarises the rail data used and the electric and fuel cell replacements.

Table 4.4: Train class data for the regional case study (Hobson et al., 2001; Alstom, 2019; Navas, 2017).

	Class 165 DMU				Class 350 EMU	iLint FC	
Carriage formation	2	3	4	5	4	2	4
Portion of distance	20%	50%	20%	10%	100%	60%	40%
Fuel consumption (kg or kWh/train-km)	0.58	0.95	1.16	1.53	6.56	0.3	0.6

4.2.3. Long-Distance Case Study

The long-distance route chosen as case study is the longest line on British rail, and is the route between Penzance and Aberdeen. This route passes through Birmingham New Street and is currently operated by Cross Country. This case study was chosen to represent long-distance travel as it is the longest single route on UK rail, and features a variety of types of terrain (from urban to quite remote). The majority of trains along this route do not travel the full distance, but instead operate between Edinburgh/Glasgow and Plymouth, though there are a number of alternative terminals, which are summarised with their frequency in Table 4.5. This is the frequency of trains coming out of New Street, though that may not be the initial service departure station, and results in an average one train per hour departing New Street in each direction.

Table 4.5: Long-distance case study service provision.

Towards Aberdeen			Towards Penzance		
Route	Length (km)	Service	Route	Length (km)	Service
Aberdeen	802	1 tpd	Penzance	507	3 tpd
Dundee	688	1 tpd	Plymouth	378	1 tph
Edinburgh	590	1 tp2h	Exeter	288	irr
Glasgow	660	1 tp2h	Bristol	160	irr
Newcastle	382	irr			
York	250	irr			
Leeds	202	Irr			

tph: train per hour / tp2h: train per 2 hours / tpd: train per day.
irr: irregular service, often extended or shortened from the usual destination.

This route almost covers the full length of the British rail network at 1,300 km, travelling through urban and rural areas. This route uses the coastal line between Exeter and Paignton, which runs directly along the waters' edge and is the only rail route into the South-West of the country. This area has seen impactful disruption due to its proximity to the sea. In 2014 for example, the coastal tracks at Dawlish were completely washed away, and it took two months for the service along this route to be restored (Network Rail, 2019c). Although this stretch of track has now been strengthened, the long-distance route is highly unlikely to ever be fully electrified due to its length, terrain difficulties, and cost. However, a proportion of the full line already features some electrification, and is possible to be further electrified for more local services, which at present the diesel-only trains cannot make use of. The route is highlighted in red in Figure 4.5 below along with the main terminal stations.

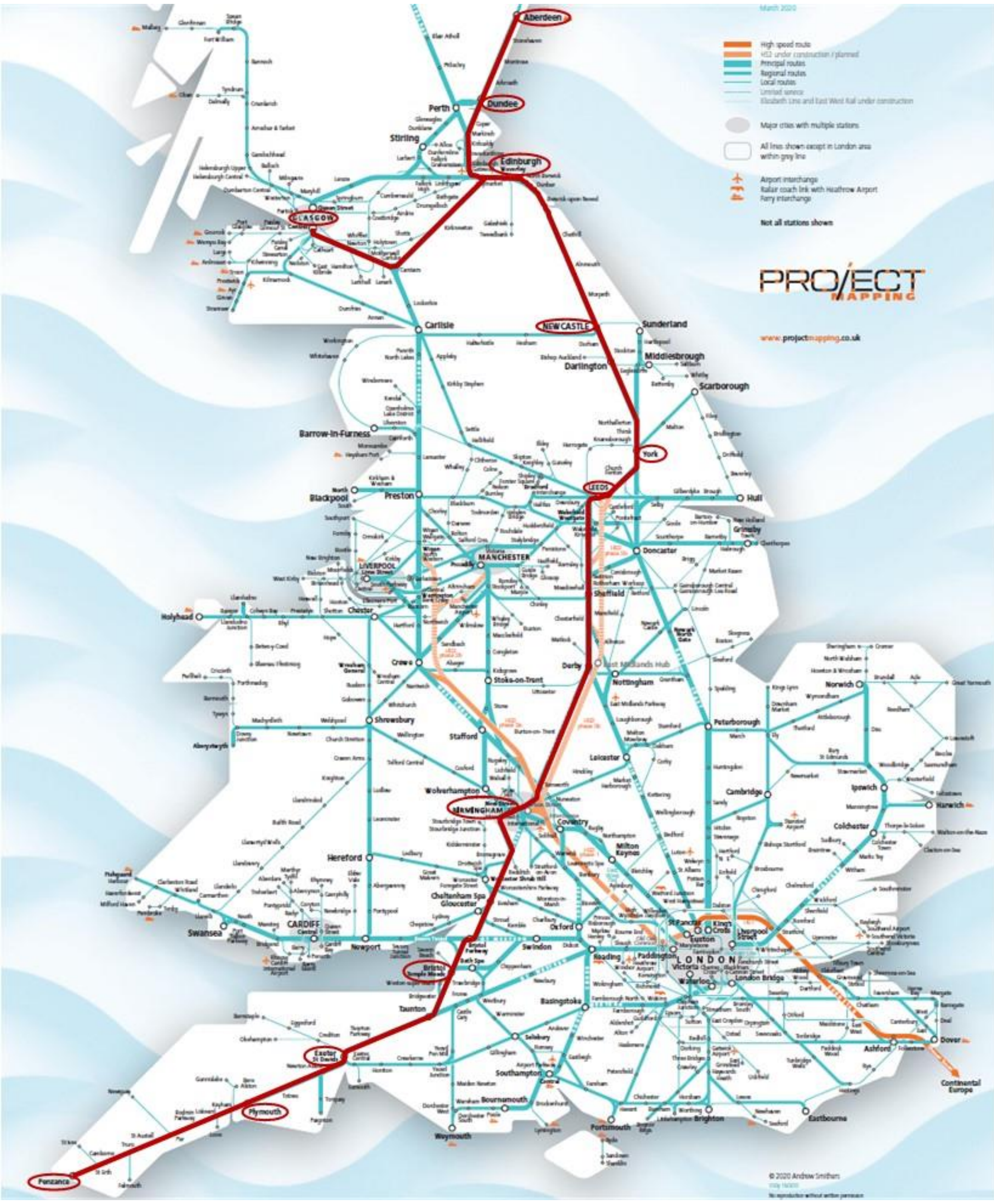

Figure 4.5: Long-distance route map (Smithers, 2020).

The trains operated along this route are mostly class 220 and 221 Voyager diesel-electric multiple units, built between 2000 and 2001. Diesel-electric trains are completely diesel fuelled, but the mechanical power is converted to electric which is what drives the train. There are also around 10 Intercity 125 trains formed of two class 43 locomotives and a group of mark 3 carriages still in use along this route, built between 1975 and 1982

(Angel Trains Ltd, 2019). In the comparison of traction technology options, the replacement electric train is based on data for a class 390, and the replacement fuel cell train is based on data for a fuel cell locomotive-driven train. Table 4.6 summarises the current rail data used and the electric and fuel cell replacements.

Table 4.6: Train class data for the long-distance case study (Hobson et al., 2001; Ruf et al., 2019).

	Class 221 DEMU					Class 43 Loco	Class 390 EMU	FC Loco
Carriage formation	4	5	8	9	10	2 loco + 8	9	2 loco + 8
Portion of distance	35%	40%	10%	5%	5%	5%	100%	100%
Fuel consumption (kg or kWh/train-km)	2.115	2.471	4.23	4.586	4.942	4.586	18.024	1.314

4.2.4. Rural Case Study

The final case study chosen is a rural route between Birmingham International and Aberystwyth/Pwllheli, passing through New Street. The section of rail between Shrewsbury and Aberystwyth/Pwllheli is known as the Cambrian Line, as it passes through the Cambrian Mountains. This route was chosen to represent the rural type of route, as it mostly runs through remote and difficult terrain (mountainous and coastal), with a majority of the route single track and low, but vital, service provision. As summarised in Table 4.7, trains typically run once every two hours (alternating hourly with the service to Holyhead via the North Wales Coast Line), and alternating between a service to Aberystwyth only, and a service to Aberystwyth/Pwllheli, dividing at Dovey Junction. This results in approximately 10 services to Aberystwyth, and 5 services to Pwllheli daily (midweek), all of which terminate and begin at Birmingham International. The route to Aberystwyth is approximately 220 km, with 60 km extra to Pwllheli.

Table 4.7: Rural case study service provision.

Towards Aberystwyth			Towards Bham International		
Route	Length (km)	Service	Route	Length (km)	Service
Aberystwyth	208	1 tp2h	Bham International	15	1 tp2h
Pwllheli	270	1 tp4h			

tp2h: train per 2 hours / tp4h: train per 4 hours.

The route passes through mountainous and remote terrain, and the section between Dovey Junction and Pwllheli runs directly along the coastline (the Cambrian Coastal Line). This section was also affected by storms in 2014, taking six months to fully reopen the line, and has more recently been closed in 2020, also due to storm damage (NR, 2014, NR, 2020a). This route features difficult terrain, is mostly on single track, and has low levels of traffic. It is unlikely to be a priority for electrification due to the terrain and the low service provision leading to comparatively high electrification costs. The route is highlighted in purple in Figure 4.6 below along with the main terminal stations.

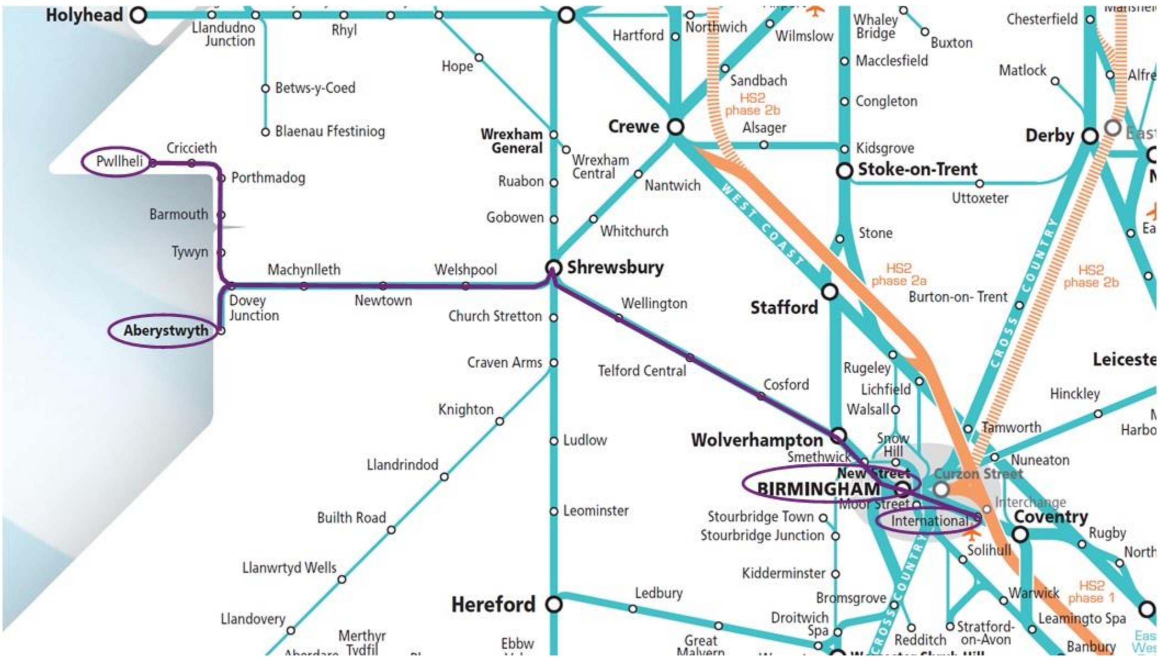

Figure 4.6: Rural route map (Smithers, 2020).

This route is operated by Transport for Wales. The trains operated along this route are class 158 trains, built between 1989 and 1992 (Angel Trains Ltd, 2019). In the comparison of traction technology options, the replacement electric train is based on data for a class 323, and the replacement fuel cell train is based on data for the iLint fuel cell train. Table 4.8 summarises the current rail data used and the electric and fuel cell replacements.

Table 4.8: Train class data for the rural case study (Hobson et al., 2001; Alstom, 2019; Navas, 2017).

	Class 158 DMU		Class 323		iLint FC	
Carriage formation	2	+2 (divide)	3	+3 (divide)	2	+2 (divide)
Portion of distance	100%	50%	100%	50%	100%	50%
Fuel consumption (kg or kWh/train-km)	0.89	0.89	9.10	9.10	0.3	0.3

4.2.5. Service Provision and Travel Distances

The analysis is based on train travel distances, so for each case study the annual distance travelled by trains in total along the route was calculated, as well as for all the routes within Birmingham city centre. To obtain data of the service provision along each route, the live train arrivals and departures from both Birmingham New Street and Birmingham Moor Street stations were recorded. Recordings were made between the hours of 5AM on Monday the 27th and 1AM Wednesday the 29th of January 2020, resulting in two full weekdays of recordings, and between the hours of 5AM Saturday the 25th and midnight Sunday the 26th of January 2020 for the weekend recordings. Scheduled and unscheduled changes to timetables are common along the railways, so the intention was to have several recording days spread out over two to three months. As engineering works around Moor Street were planned for the months of February going in to March, the end of March was to be the next recording period - at which point the train services, including the timetable information available, changed due to the Covid-19 outbreak. The timetables recorded in January have been cross-checked with the National Rail scheduled timetables where any anomalies were identified, however the distance travelled has only been calculated using this one recording set and so may be less reliable than if multiple recordings had been made. This is likely to produce an underestimation of the absolute values as there may be timetabled services which did not occur, but the aim of comparing between train technologies remains valid as they all use this same basis for analysis. This method of data collection enabled a bottom-up, accurate definition of the routes studied, accounting only for the geographically defined case studies of interest, and eliminating the need to estimate the cases as a proportion of TOC route covered.

The live timetable recordings were made using the Live Departures and Arrivals pages on the National Rail website (National Rail, 2021). The first step was to identify the destinations and origins relevant to each case study, and count these to find the number of daily services. The length of track between stations was estimated using the directions function on Google Maps (Google, 2021), with the route set to follow the railway as closely as possible. These results were then used to calculate the distance travelled daily by the number of services recorded. The annual distance was calculated with the assumptions that the trains run as normal for 52 annual weekends, and 255 out of 261 annual weekdays. The reduced weekdays is to account for bank holidays and engineering works, with reduced service levels. Details of the collected distance data showing the estimated track lengths, measured number of trips, and daily and annual distances calculated can be found in Appendix 1, A1.1. Table 4.9 shows a summary of the average weekday travel distance, the average weekend (Saturday and Sunday together) distance, and the estimated annual distance.

Table 4.9: Travel distance summary.

Case Study	Weekday Distance	Weekend Distance	Annual Distance
Birmingham City	9,810 km	13,000 km	3,180,000 km
Regional	12,400 km	12,900 km	3,830,000 km
Long-Distance	30,000 km	52,900 km	10,400,000 km
Rural	6,680 km	11,500 km	2,300,000 km

4.3. Literature Resource Collection

The collection and analysis of secondary data is significant for this research. The collected data can be organised into three categories: emissions profiles, monetisation of impacts, and costing data. The resources are all deemed to be reliable, as they are from reputable sources. The majority of data was collected from Government Departments such as the Department for Business, Energy and Industrial Strategy or the Department for Environment, Farming and Rural Affairs, or from independent organisations such as the Office of Rail and Road, consultancy projects for the UK Government, peer-reviewed research papers, and conference proceedings. Assembling these different sources of information together provided sufficient data with which to explore the external and internal dimensions of cost for rail. Data was collected using internet search engines and journal searches such as Science Direct, exploration of the data.gov.uk and Office of Rail and Road websites, following up reference lists, and some contact following a brief external project with a rail consultancy company. The use of secondary data sources is a necessary and valid method to investigate the aim and objectives of this research, but it is also important to be aware of potential sources of unreliability or bias in data collection.

The main data category where bias may be prevalent is for the costing data, where costs may be reported to fit a given agenda, and there is no way of determining whether the cost data given genuinely reflects costs paid. Specifically, the reports which gather purchase prices for diesel, electric, and fuel cell trains, generally study fuel cell rail implementation and so may be reporting 'future' purchase prices for fuel cell rail, which are lower than the actual prices paid. This is balanced by elements of the analysis, which aim to overestimate the figures for fuel cell rail in an attempt to ensure the findings from the cost analysis are robust. Namely, an underestimation of maximum fuel cell train range is deliberately used, to counter potential underestimation of train prices.

In some cases relevant data could not be found, in these cases numbers were estimated based on alternative data. A lack of available data seems common amongst sustainability assessments, and is to be expected where potentially commercially sensitive and non-existent information is required (Bebbington and Gray, 2001; Herbohn, 2005; Frame and Cavanagh, 2009; Esters and Marinov, 2014). Emission factor data for specific British train classes is not routinely calculated, as there is no need for such data within the rail industry. Pricing data for the operational costs of rail also proved difficult to find, though this barrier was overcome by using alternative data which could be found and building up a picture of operational costs. For example, instead of finding operational fuel cost data for the rail industry, the analysis calculated the operational fuel costs based on train fuel consumption data and estimated fuel prices.

The resources collected for secondary data are summarised in Table 4.10, categorised under emissions analysis, emissions monetisation (external costing), and pricing information (internal costing). Some references were used under more than one category, but these are only placed once under the category which appears first in the table. The purpose and source of each resource is clarified, along with the type of data extracted. Detailed tables of the data numbers extracted are contained within the Appendices of this thesis. The emissions analysis data can be found in Appendix 2, the emissions monetisation data can be found in Appendix 3, and the pricing data can be found in Appendix 4 for capital costing, and Appendix 5 for operational costing.

Table 4.10: Summary of secondary resources.

Reference	Resource purpose	Resource Type	Data Extracted
Emissions Analysis			
Hobson et al., 2001	Analysis of rail emissions	Consultancy report	Train emissions factors Fuel consumption factors
Chernyavs'ka and Gullí, 2009	Comparison of road vehicle internal and external costs	Published journal article	Diesel and H_2 fuel production emissions
BEIS and DEFRA, 2019	Greenhouse gas reporting	Government statistics	Greenhouse gas conversion factors
Emissions Monetisation/External Costing			
Bickel and Friedrich, 2005	ExternE report	Methodology report	Monetisation of impacts
Korzhenevych et al., 2014	HECT report	Methodology report	Monetisation of impacts
DfT, 2021b	Greenhouse gas valuation	Transport Analysis Guidance	Carbon emissions monetisation
Pricing Information/Internal Costing			
Kent et al., 2016	FC train demonstration project	Academic and industry project	Train specifications FC train purchase pricing H_2 infrastructure pricing
Pettit, 2017	FC train case study	Academic project	Train specifications DMU purchase pricing Electrification pricing Diesel pricing

Summary of secondary resources continued.			
Reference	*Resource purpose*	*Resource Type*	*Data Extracted*
Navas, 2017	Business case for FC trains	EU industry project	FC train specifications FC train purchase pricing DMU, EMU & FC train maintenance pricing Infrastructure maintenance pricing
Ruf et al., 2019	Cost analysis for FC projects in EU	EU project	FC train purchase pricing FC train maintenance pricing
Bünger, 2017	FC train test projects report	Company report	FC train specifications FC train purchase pricing Hydrogen pricing
Jan et al., 2011	Analysis of rail value for money	Consultancy report	DMU purchase pricing EMU purchase pricing
Porterbrook, 2014	Class 172 brochure	Brochure	DMU train specifications
Butcher, 2017a	Overview of electrification projects	Commons Library briefing paper	Electrification pricing
Marin et al., 2010	Rail cost analysis	Published journal article	Electrification pricing FC train purchase pricing
Zschoche et al., 2012	Comparison of rail costs in the UK and rest of Europe	Consultancy report	DMU maintenance pricing EMU maintenance pricing
Network Rail, 2020b	Track access charges	Industry data	Track access charges
BEIS, 2020b	Road fuel and petroleum prices	Government statistics	Diesel pricing
RAC Foundation, 2020	Diesel pricing information	Statistics	Diesel pricing
BEIS, 2020c	Non-domestic electricity and gas prices	Government statistics	Electricity pricing Gas pricing
BEIS, 2020d	Domestic electricity prices	Government statistics	Electricity pricing
Ofgem, 2020	Wholesale pricing charts	Statistics	Electricity pricing

Summary of secondary resources continued.			
Reference	*Resource purpose*	*Resource Type*	*Data Extracted*
California Fuel Cell Partnership, 2016	FC vehicle refuelling costs	Community for FC vehicle owners	Hydrogen pricing
Hydrogen Europe, 2020	FC demonstration project	Industry data	Hydrogen pricing
Timperley, 2019	Cost competitive renewable H_2	Published journal article	Hydrogen pricing
Walker et al., 2018	Hydrogen costing analysis	Consultancy report	Hydrogen pricing
BEIS, 2021	Renewable load factors	Statistics report	Renewable project pricing
Catapult, 2019	Wind farm costs analysis	Consultancy report	Wind farm project pricing
Renewables First, 2015	Wind turbine cost analysis	Renewables company	Wind farm project pricing
Solar Trade Association, 2016	Solar farm cost analysis	Consultancy report	Solar farm project pricing
Sunstore, 2020	Solar farm cost analysis	Solar company	Solar farm project pricing

The majority of data sources were published within the last 10 years, with the main exception of Hobson et al. (2001), which contains the majority of emissions and fuel usage data that could be found. This is a reasonable timeframe for data collection, as most timescales related to British rail are long-term, due to the nature of longevity of infrastructure, rolling stock and equipment. For example, a minimum train life is around 30 years (often significantly more), and franchise agreements tend to run for around 10 years (and are often renewed with the same Train Operating Company). For regularly updated data sets, the most up to date data values available at time of data collection is used, up to the end of 2019. All monetary values are converted to 2020£ using both historical inflation (Webster, 2020), and currency change (Exchange Rates UK, 2020) information found online. There is reasonable concern that the use of emission factors published in 2001 could lead to inaccurate emissions reporting, especially as since that date regulations have been implemented to limit the emissions from train engines. However, the trains studied in this analysis were built before 2001 (with the exception of 172, but 165 data is used as discussed in Section 4.2.2), and so the main differences would be expected from the desulphurisation of diesel fuel. Furthermore, the focus of this study is a comparison of rail traction options and illustration of the impacts, not an evaluation for emissions reporting which would require greater involvement from industry.

Data was extracted from a total of 30 different sources, covering emission factors, impact monetisation, capital costing, and operational costing elements for diesel, electric and fuel cell trains. The majority of data used fits the definition of robust data being from credible sources, as it is mostly from UK Government or affiliated sources, or peer-reviewed sources. The data is thus suitable for evaluating the emissions, external costs, and internal costs for the three case studies, thus enabling to evaluate the objectives and address the aim of this thesis. The rest of this chapter addresses the analysis of collected data, beginning with the assessment of emissions and their impact.

4.4. Impact Assessment

4.4.1. Emissions Analysis

Determining the emissions from rail is one objective of this thesis. The emissions are evaluated to provide a means of comparing the impacts of the three traction options of diesel, electric, and fuel cell rail, and so that the emissions can be monetised for inclusion in the examination of external costs. Rail emissions are also evaluated for the case of Birmingham city centre, to illustrate the impact of rail emissions in an urban environment. The emissions evaluation does not cover all emissions, as the pollutants considered depends upon the emission factors for rail which could be found in the literature, which are detailed in Appendix 2. Availability of different data from different sources, means some emission factors have been assumed equivalent, such as values for SO_2 and SO_x, or CO_2 and CO_2e. The emissions assessed in the evaluation are:

- Carbon dioxide (CO_2) or carbon dioxide equivalent (CO_2e) - for diesel 98.7% CO_2, 0.0116% methane (CH_4), and 1.32% nitrous oxide (N_2O) (BEIS, 2019a),
- Sulphur dioxide (SO_2), or sulphur oxides (SO_x),
- (Non-methane) Volatile organic compounds (NM VOCs) such as benzene and 1,3-butadiene,
- Carbon monoxide (CO),
- Particulate matter (PM), or particulate matter smaller than 10 microns (PM_{10}),
- Nitrogen oxides (NO_x).

This is not an exhaustive list of the emissions from rail travel, but it covers the focus of global warming gas (CO_2), and the gases of interest in air pollution as categorised by the EURO vehicle emissions standards (NO_x, CO, HC, PM). The most notable omission from this list is smaller particulate matter, $PM_{2.5}$, which has significant health impacts as these particles are small enough to penetrate through the lungs and into the bloodstream, but no data could be found for this. Due to the monetisation values and methodologies used, in the evaluation of emission impacts, CO_2 emissions are assumed to mainly have impacts at a global level, while the other emissions are assumed to have localised impacts (in practice these also have global warming impacts, many more impactful than CO_2, although are not released in as high volumes).

The emission factors for diesel trains at use, electric train electricity use, and some factors for the UK electricity grid were obtained from the *Rail Emission Model* from Hobson et al. (2001). Although this report is 20 years old, it remains the most complete and accessible set of emission factors, and covers all of the train classes of interest as these were built before 2001, except for the class 172 which were built from 2010 to EURO standard IIIA regulations. The data from Hobson is derived from a combination of previous direct measurement studies, manufacturer data, and fuel consumption data, and includes the impact of stopping and average journey profile, specific to local, regional, and locomotive routes. This was also the data used by the National Atmospheric Emissions Inventory (NEAI) until 2018. In June 2020 the Rail Safety and Standards Board (RSSB) published an update to rail emission factors, which was the first update since the 2001 report. If calculating emissions within the rail industry, the RSSB report provides more up to date factors which are based on the train engine notch data, available from each train based on its direct real-time operation. Unfortunately, this information is not widely available and so although these emission factors provide a greater level of detail, and allow for very specific emissions analysis (within stations for example), they cannot be used for this analysis (but would be recommended within the rail industry). The RSSB report (2020) gives some updated values used by NEAI, developed by RSSB, which Table 4.11 below compares with data from Hobson et al. This does not include data for the class 220 or similar higher-speed multiple unit, so the class 150 is illustrated, just as a means of comparing the two resources.

Table 4.11: Comparison of Hobson et al. (2001) and RSSB/NEAI (2020).

Pollutant (g/train-km)	Class 165 (2-car)		Class 150 (3-car)	
	NEAI (2018)	Hobson et al. (2001)	NEAI (2018)	Hobson et al. (2001)
CO_2	/	1824	/	3203
SO_2	/	2.3	/	4.1
VOCs	0.9	1.8	0.3	3.1
CO	7.9	1.8	1.6	3.2
PM_{10}	0.16	0.6	0.08	1.1
NO_x	1.4	18.6	5.2	32.6
Hydrocarbons	1	/	0.3	/

This table shows that the updated values are quite different to the values from Hobson et al., but they give no value for CO_2 emissions (or fuel usage), which is a significant omission in addressing climate change impacts. SO_2 is no longer covered in this emission factors as this is dependent on the fuel, and since 2001 the sulphur content of diesel has reduced, with the latest 2010 regulations limiting sulphur content to 10ppm (mass basis, RSSB, 2020). This shows that the emissions used in this analysis may be overestimated, and this will be discussed further in Chapter 5.

Fuel cell trains are evaluated with seven different hydrogen production options, listed below. These production options were chosen to reflect the range of ways hydrogen is most likely to be acquired in a fuel cell rail system. There is an emphasis on hydrogen produced with renewable electricity, as the ‘gold standard’ for hydrogen production. Renewably-produced hydrogen is assumed to not produce any emissions within this analysis. In practice, there would be some emissions, for example from transport for maintenance purposes, however these have been deemed outside the scope of emissions analysis, as these elements are also not included in the analysis for any other fuel production method. Although hydrogen is produced at industrial scales from the gasification of coal, this option has not been included as it produces a high volume of emissions. The data assumes that offsite (imported) hydrogen production is at centralised industrial scales, and includes an account for transport. Onsite hydrogen production is at a small scale which only produces the hydrogen needed, and does not require transport. The sources of hydrogen studied are:

- Imported hydrogen produced from steam methane reforming (SMR),
- Imported hydrogen produced from electrolysis with European Union average grid electricity,
- Onsite production via steam methane reforming, with UK gas grid methane,
- Onsite production via electrolysis, with UK grid electricity,
- Onsite production via electrolysis, with solar power,
- Onsite production via electrolysis, with onshore wind power,
- Onsite production via electrolysis, with offshore wind power.

The boundaries of emissions analysis are air pollutant emissions from fuel production (upstream) and at point of use in train propulsion (downstream). The upstream fuel production emissions for diesel and hydrogen were obtained from Chernyavs'ka and Gullí (2009). Table 4.12 summarises the elements included in the emissions analysis along with the input data from which the emissions analysis is built up. The analysis is based on the distance travelled in total on each route annually, scaled up to a 30-year lifetime. The input data can be found in Appendix 1, A1.1. for travel distances, A1.2 for fuel consumption rates, and Appendix 2, A2.1 for train emission profiles, A2.2 for electricity emissions, and A2.3 for fuel production emissions. The next stage in the evaluation is to monetise the impacts of rail emissions, and this is the subject of the next section.

Table 4.12: Emissions analysis categories.

Emissions Category	Input Data	Comments
Upstream		
Diesel production	Diesel consumption rates Travel distances Upstream emissions profile	
Hydrogen production	H_2 consumption rates Travel distances Upstream emissions profile	Including different sources of H_2 production
Electricity production	Electricity consumption rates Travel distances UK grid emissions profile	These are defined as at-use emissions, but are not produced locally to the case study
Downstream		
Diesel combustion	Train class emissions profile Travel distances	Only technology with proximate at-use emissions

4.4.2. External Costing Analysis

The procedure for external cost analysis was introduced in Chapter 3, Section 3.4, and this introduced the three layers of external cost analysis as follows:

- Emissions analysis,
- Modelling the impacts of emissions, and
- Monetisation of the impacts.

A selection of external cost analysis methodologies were also reviewed in Section 3.4.4. Two of these methodologies are selected to evaluate the external costs from rail emissions in this research: The External Costs of Energy (ExternE), and the Handbook on External Costs of Transport (HECT). Both of these resources were created for the European Commission, and both are focused on the localised impacts of air pollution. They differ, however, in which sources of emissions they were designed to evaluate, and differ in the layers of analysis included in the methodology. The ExternE methodology can evaluate emissions from any defined source, and contains two analysis layers, namely modelling the impacts of emissions and monetising the impacts, meaning the emissions analysis must be completed separately. The HECT methodology specifically evaluates transport emissions, and contains all three layers of analysis, basing the evaluation on travel distance data rather than calculated emissions data.

These two methodologies were selected as they are the two most appropriately applicable to the situation being investigated in this thesis. The ExternE methodology allows for evaluation of the external costs based on direct emissions, meaning this methodology can be applied very specifically to the situation being studied. The HECT methodology also has this level of specification, as the evaluation is based on travel distances which can be case-study specific. Alternative models found within the methodological research are focused on transport systems either at a regional or national level, which does not allow the degree of specificity required for the focus of this research. Although the two methodologies evaluate the same impacts, they are expected to give different results. This is because they differ in how each methodology is used, including the type of input data, and the internal data and procedures are different. Using two different methods to evaluate external costs gives an idea of the potential range of external costs, rather than attempting to define a single answer. The results of the external cost analysis are treated as a range of possible answers in the results. This is to demonstrate that externality evaluation is inherently uncertain.

While both methodologies focus on the localised impacts of emissions, neither includes monetisation of carbon dioxide release and global warming impact. As carbon dioxide is the most voluminous emission from transport, this is a significant omission, so in addition carbon costs are monetised using the UK Department for Transport WebTAG (Transport Analysis Guidance) values for emissions appraisal (DfT, 2021b).

ExternE/EcoSenseLE

The ExternE project (Bickel and Friedrich, 2005) is the most widely used method of external cost analysis. ExternE has regularly been used to estimate the external costs from electricity production, both for specific projects (Holmgren and Amiri, 2007), and at a country or even worldwide level (Klaassen and Riahi, 2006; Nguyen, 2007; Rafaj and Kypreos, 2006; Thopil and Pouris, 2015). This methodology has also seen some use in the transport sector for examining external costs (Chernyavs'ka and Gullí, 2009; Tzannatos, 2009 & 2010).

The ExternE monetisation method follows the Impact Pathway Assessment approach: specification of emissions, modelling of emission dispersion, evaluation of impact damages, and valuation of impacts (Bickel and Friedrich, 2005). The ExternE methodology and data has been integrated into an online model called EcoSenseLE, which evaluates the external costs based on input emissions. The EcoSenseLE model was managed by the Institute of Energy Economics and Rational Energy Use (IER) at the University of Stuttgart (©2017). The online model used within this methodology was terminated in January 2021, however the EcoSense cost factors have since been integrated into a new OpenEnergy Platform, with aim to provide transparency and cooperation in energy research, available from https://openenergy-platform.org.

To evaluate the external costs using the ExternE methodology integrated into the EcoSenseLE model, first the emissions are calculated as detailed in Section 4.4.1. Within the online model, the scenario is set up for the additional emissions in Great Britain set for the 'future' reference year of 2020, which accounts for developments to emissions reduction and increase in the cost of emissions as was expected, shown in Figure 4.7. The calculated emissions data is input, as shown in Figure 4.8. The example shown in Figure 4.8 is the annual output for diesel train at-use emissions on the regional route, so the calculated emissions are NO_x, PM_{10}, SO_2, CO, and NM VOCs, and all are an urban low-level release. The long-distance case study assumes 30% urban low-level and 70% rural low-level release, and the rural case study assumes 20% urban low-level and 80% rural low-level release, based on observations of the Google Maps data for case study routes, and estimation of the route distance passing directly through urban and built up areas. Again, this data aims to enable comparison between propulsion modes, not evaluate an absolute external cost. The complete list of pollutant inputs in Figure 4.8 has been redacted for ease of demonstration, but in total this form allows input of 37 possible pollutants for impact analysis (which does not include CO_2). The model then computes the impacts based on the input data and the ExternE monetisation data which is displayed in Table 4.13. The results are given as shown in Figure 4.9. The health impacts are given in both Disability Adjusted Life Years (DALYs), and monetary value, and the impacts on crops, materials, and ecosystem quality losses are all given in monetary value. The monetary value is in 2010€, so for the final results these are converted to 2020£, and DALYs are not used within this research. ExternE allows for the positive impact of nitrogen fertilising effects on crops (under the assumption there is not already an excess of fertiliser applied to the crops), so the value for crop losses has a +ve or -ve to indicate the impact. In this case, the -ve symbol indicates a positive fertilising effect from NO_x emissions (Bickel and Friedrich, 2005). This positive effect is taken into account within the total external cost values reported in Chapters 5 and 6, but as Figure 4.9 shows, this positive fertilising impact is small compared to the negative impacts on health and ecosystem losses.

Table 4.13: ExternE monetisation data for external costs in EcoSenseLE (IER, 2017).

Category	Region	Year	Indicator	Value	Unit
Health externalities (unit costs)	UK	2020	NO_X	8.244516	Euro/kg
Health externalities (unit costs)	UK	2020	SO_2	24.12156	Euro/kg
Health externalities (unit costs)	UK	2020	NMVOC	2.022928	Euro/kg
Health externalities (unit costs)	UK	2020	PM_{10}	2.662229	Euro/kg
Health externalities (unit costs)	UK	2020	$PM_{2.5}$	62.02373	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	NO_X	8.361487	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	SO_2	24.21003	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	NMVOC	2.124727	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	PM_{10}	2.665421	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	$PM_{2.5}$	62.37561	Euro/kg

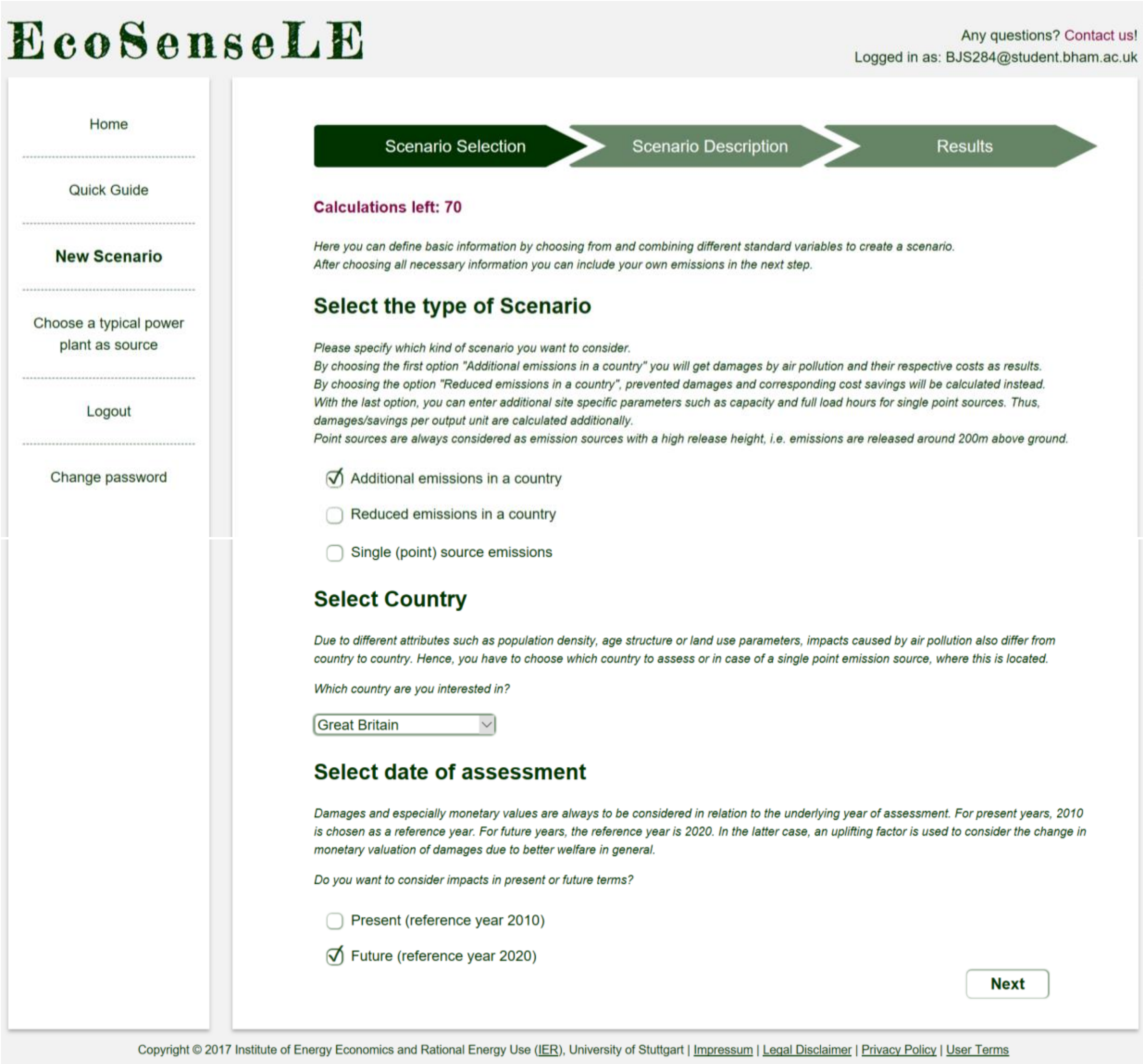

Figure 4.7: EcoSenseLE scenario specification (IER, 2017).

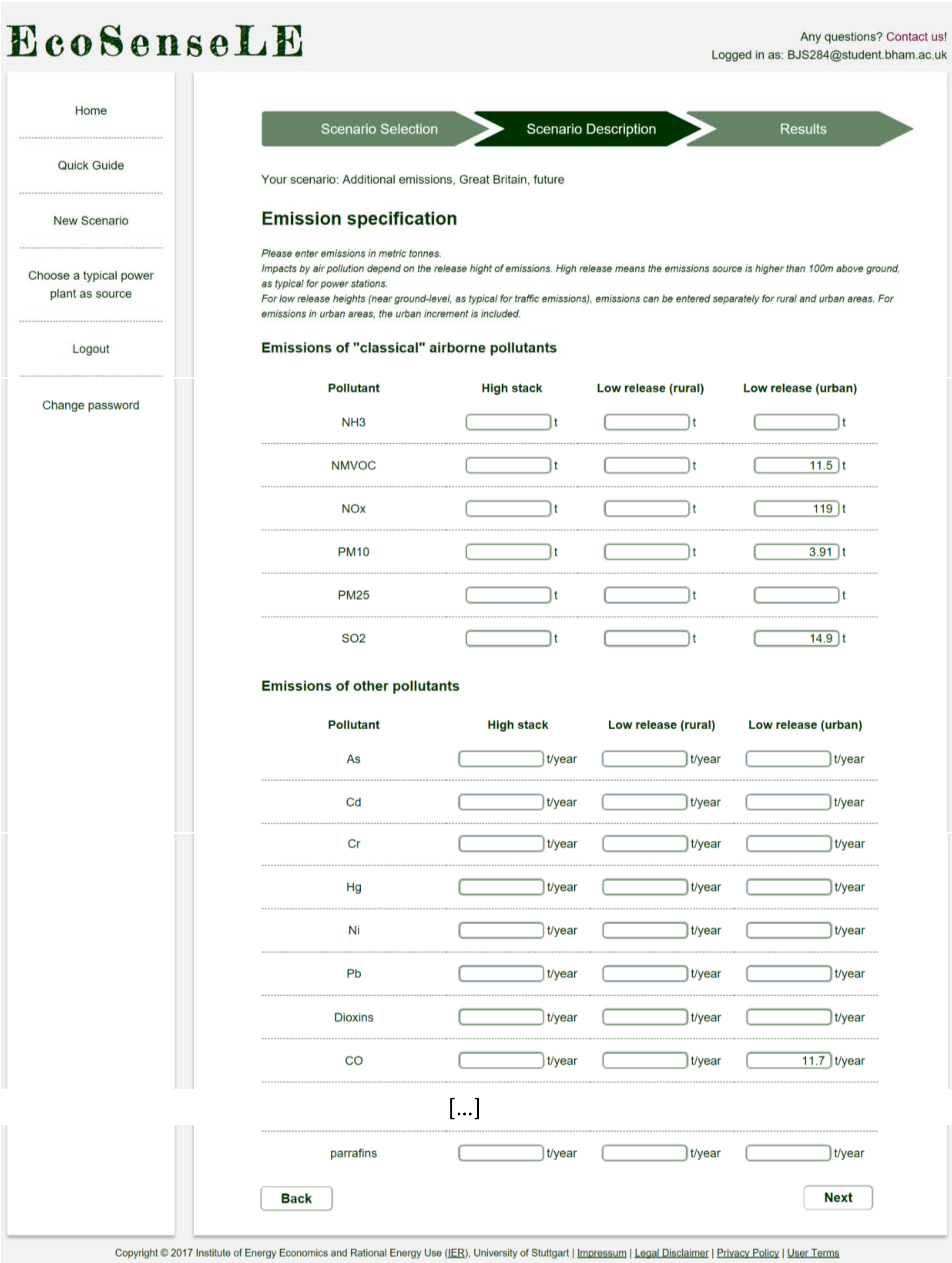

Figure 4.8: EcoSenseLE emissions specification (IER, 2017)

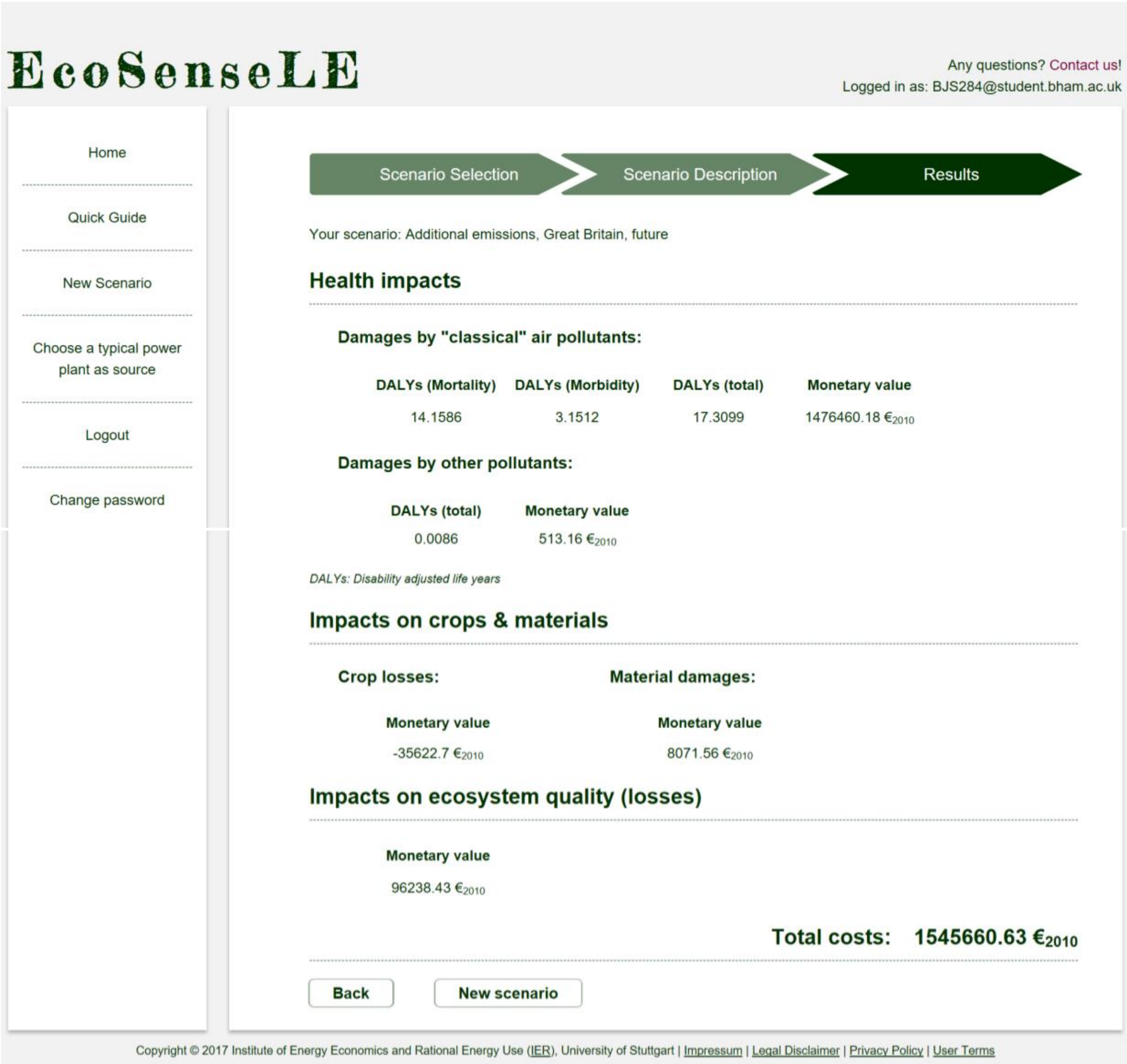

Figure 4.9: EcoSenseLE results (IER, 2017).

Handbook on External Costs of Transport

HECT (Korzhenevych et al., 2014) is a less well known and used method of external cost analysis. As it was created solely for the purpose of estimating transport costs, it is a relevant method to use in parallel with ExternE. HECT analysis is available at three levels of detail, and for this thesis only the first, least detailed level is used as it is widely available for use. This approach is justified within the wider context of this thesis however, as it allows for a broad outline of externalities and a comparison with the ExternE results, but without the detail and expense required for a more in depth evaluation.

The method for using HECT is based on train type and travel distance. HECT provides Microsoft Excel spreadsheets for different transport categories, which contain calculated external cost factors for air pollution impacts. The external cost factors are specific to each EU country. The factors are available for two propulsion options, electric and diesel, and for multiple unit (MU) type trains and locomotive type trains. Additionally, HECT includes data for high speed electric rail, though this is not a feature of any of the case studies. For each type of train the data is also divided into urban, suburban, and rural train operation. However, this method does not allow for distinction between the types of trains or carriage numbers within each category, and the external cost data is given per train (not per carriage). Table 4.14 shows the data for external costs of air pollution for trains in the UK, given by the HECT methodology. As with ExternE, the data is given in 2010€/train-km, so this was converted into 2020£/train-km for analysis.

Table 4.14: HECT data for the United Kingdom (Korzhenevych et al., 2014).

		Air pollution external cost (€ct/train-km)		
Type of Train		Urban	Suburban	Rural
Passenger Diesel	Locomotive	240.6	112.0	90.4
	Railcar (MU)	204.5	87.8	63.9
Passenger Electric	Locomotive	116.9	28.5	8.4
	Railcar (MU)	116.9	28.5	8.4
	High-speed	/	/	14.0

Carbon Costing

Carbon dioxide is included in the external cost analysis for this research but is done independently of the two resources above. Monetisation of CO_2 (or carbon) costs was evaluated using the UK Government WebTAG carbon valuation (DfT, 2021b), which gives transport appraisal guidance, including CO_2e non-traded cost values in £/tCO_2e up until the year 2100. CO_2e refers to carbon dioxide equivalent, and includes all greenhouse gases as covered by the Kyoto protocol (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphurhexafluoride). As it relates to diesel, CO_2e is 98.6% CO_2, 1.3% methane, and 0.1% nitrous oxides. For some of the emissions analysis, data is given in CO_2e and does not separate out the CO_2, so these have been deemed interchangeable, and throughout this thesis CO_2 and CO_2e are used interchangeably. In practice, this means that for some cases the 'carbon cost' refers to CO_2, and in others $CO_2+CH_4+N_2O$. The costs also provide low, central and high values. The WebTAG greenhouse gas emissions valuation is based on a marginal abatement cost approach, consistent with Government emissions targets (DfT, 2021b). The full set of CO_2e costs from 2020 up until 2050 can be found in Appendix 3, A3.4.

4.5. Financial Evaluation

The viability of fuel cell trains on the British network is explored by executing a financial appraisal of relevant costs. This financial assessment evaluates relevant internal costs, that is capital and operational costs. Relevant costs means only costs which change across the three technology options being explored. The internal costs are then examined alongside the external costs calculated, to include the monetary impact of emissions into Overall Costs, for comparison of rail traction options. The Lifetime Cost analysis is based on the internal costs over a 30-year rolling stock lifetime timeframe. This addresses the aim of exploring the internal and external dimensions of cost, the objectives of evaluating internal and Lifetime Costs, and allows for comparison between rail technology options based on cost and impact of emissions. This comparison is made on a cost basis rather than ownership cost basis, because as the overview of the rail industry in Britain in Chapter 2 showed, there are different parties involved in rail ownership and expenditure.

The financial assessment performed in this research therefore impacts different stakeholders. The results of the Lifetime and Overall financial assessments are presented in Chapter 6.

4.5.1. Internal and Lifetime Costing Analysis

Capital and operational costs form the internal cost analysis. The capital costs are calculated as a one-off payment, and the operational costs are evaluated over the 30-year defined lifetime basis, which results in the Lifetime Costs. The analysis is based on current service provision and the elements needed to maintain that provision. This means that if the current level of service that is provided by diesel trains can be provided by a lower number of electric trains, due to their improved reliability and the fact that electric trains do not have a maximum fuel mileage, then the electric capital cost is based on the estimated lower number of trains. The analysis is built up from the costing values which were gathered from resources as detailed in Table 4.10, in Section 4.3. These costing values (or input data) are separated into the categories presented in Table 4.15, which shows which capital and operational cost categories were included in the analysis, and what type of input data was used to estimate each cost category. Detailed recording of the data used can be found in the Appendices. Appendix 4 contains the data used to calculate the capital costs, and Appendix 5 contains the data used to calculate the operational costs.

Table 4.15: Internal cost analysis categories.

Cost Category	Input Data	Comments
Capital		
Train	Train purchase costs Fleet numbers	Use of current fleet numbers, and estimating minimum
Track infrastructure	Electrification project costs Track lengths	Only for electric
Refuelling and fuel production infrastructure	H_2 refuelling infrastructure costs H_2 production facility costs Renewable energy costs Fleet numbers & fuel consumption	Only for fuel cell
Operational		
Fuel/Electricity	Diesel/H_2/electricity prices Train fuel consumption Travel distances	Wholesale & customer pricing to estimate industry pricing
Maintenance - train	Frequency and prices Travel distances	For all
Maintenance - infrastructure	Frequency and prices	For refuelling facilities and electric infrastructure
Track charges	Track charges Travel distances and fleet	For all

4.5.2. Overall Costing Analysis

The Overall Cost analysis is the combination of external and internal costs, over the 30-year lifetime. Calculating the Overall Costs is the final objective before examining the implications of the analysis results. The Overall Cost Analysis combines all of the analysis of costs into summative numbers, which are used to compare between rail technology options in a manner that includes the impacts from emissions. This comparison shows which technology is the most cost-effective in a situation where market pricing comes to reflect the true cost of activities, that is including the external costs. In summarising internal and external costs into Overall Costs, some of the costing and impact detail is lost, so the Overall Costs are used as another form of presenting the information, but the detail is most important, so Overall Costs should not be highlighted out of context.

4.6. Summary

This chapter described the methodological procedure this thesis follows in order to address all but one of the research objectives defined in Chapter 1. As was detailed in the introduction to this chapter, the methodological procedure is based on a four-step approach to FCA, proposed by Bebbington et al. (2001), which outlines the process for accounting for all internal and external financial inputs and outputs of a system. The aim of this thesis analysis is to enable an exploration of the internal and external costs of rail. Case studies were first defined, as the boundaries limits to the analysis. Three case study routes form the basis for analysis, defined as a regional route, a long-distance route and a rural route, and were selected in order to represent the types of rail route and service provision found in British rail. The three case study routes are centred on Birmingham city, and an analysis and monetisation of the emissions from rail within Birmingham is also undertaken to give further insight into the impact of rail in an urban environment.

The collection of primary and secondary data was surveyed in this chapter, and bringing this wide array of data together enables the analysis of data to pursue the research objectives. The objectives of calculating the emissions from rail, and evaluating the impacts of emissions through external cost analysis are treated together in this analysis, and form the basis for Chapter 5. The process of calculating emissions and evaluating the external costs is applied to the three options for rail traction, namely diesel, electric and fuel cell (with hydrogen production options), and to the three case studies, to evaluate the relative impact of each technology. Finally, the financial analysis process is outlined, which considers the objective of evaluating the internal costs for rail traction options and for the three case studies, in order to compare the options on a cost valuation basis. The analysis of internal costs and Overall Costs is the subject of Chapter 6. The objective which is not addressed in the analysis results in the next two chapters, namely examination of the implications of the results for rail decarbonisation in Britain, forms the basis for Chapter 7.

CHAPTER 5: RESULTS - EMISSIONS AND EXTERNAL COST ANALYSIS

5.1. Introduction

This chapter is the first of two which present the results of the analysis, for which the procedure was detailed in Chapter 4. This chapter addresses the research objectives of evaluating the emissions from rail, and evaluating the impacts of emissions through external cost analysis. Evaluating the emissions and their monetised impacts is the first part of examining the Overall Costs of rail, focusing on the external costs. This gives a means of comparing the options for traction technology based on the production of emissions, and the impacts of these emissions.

The first part of this chapter presents the results of the analysis of emissions and the analysis of external costs from rail within Birmingham city centre. This example illustrates the impact of rail, based on the traction mix of diesel and electric rail which is prevalent in Britain. Although rail is one of the most sustainable forms of transport, due to its capacity to transport high numbers of passengers, evaluating the emissions and their impacts within Birmingham shows that there is potential to reduce the impact of rail and improve the sustainability of this transport mode further. The second part of this chapter develops the analysis of the emissions produced, and the analysis of external costs, for the three case studies. This analysis produces a comparison between the options for rail traction based on the emissions produced by each technology, and the impacts of those emissions from external cost analysis. This comparison gives the first findings for this research, that is the evaluation of which rail technology option produces the least emissions, and is the most environmentally sound within the boundaries of this analysis.

The final part of this chapter discusses the implications of evaluating the external costs of rail. Monetisation is not an exact method of analysis. As was developed in Chapter 3, monetisation methods often rely on subjective data. This is by nature a feature of external cost evaluation, as the costs considered do not have a market value, which is what makes them external costs. Monetising impacts enables them to be included into financial calculations for consideration of all costs involved in an activity. This final section discusses the potential impact the internalisation of externalities could have on the British rail network. The external cost evaluation methods used in this analysis focus on local impacts of air pollution (discussed in Chapter 4, Section 4.4.2), so the role of locality in external costing is also explored. This chapter presents the first part of the analysis results, focused on emissions and their impacts, beginning with the analysis for the urban environment of Birmingham city centre.

5.2. Illustration of the Impact of Rail

5.2.1. Rail Emissions within Birmingham

In addressing the research objective of evaluating the emissions from rail, this first section presents the results of calculating the emissions from rail within Birmingham city centre. The purpose of this example is to give an idea (albeit approximate, due to the nature of external costing) of the economic impact of rail in its present traction technology mix. In this intention, rail in Birmingham is a mix of diesel and electric, representative of UK rail. For this evaluation, the emissions and impacts were calculated over the course of a year only, not the 30-year lifetime. In order to calculate the emissions accurately, information was collected regarding the types and classes of trains which run through Birmingham, and an evaluation of the distances travelled by each type of train was undertaken. This gave results for the distance travelled by each type of train, within Birmingham, for a representative year of operation based on the data collected in February 2020 (year 2020 pre-pandemic, Chapter 4, Section 4.2.5). The emissions produced by each type of train were then calculated by using the emission factors for diesel trains, the electricity grid, and upstream diesel, which are detailed in Appendix 2, A2.1, A2.2 and A2.3. Equation 5.1 shows the basic equation that was used for calculating rail emissions, based on emission factors per train-km, and the train-km travelled. This is followed by an example calculation for one train class on one route within Birmingham City centre.

$$Emission\ (g) = emission\ factor\ (g/t-km) \times distance\ (t-km) \qquad \ldots(5.1)$$

Example calculation

- Class 159 Diesel Multiple Unit between Moor street and Yardley Wood
- Annual distance travelled between Moor Street and Yardley Wood by Class 159: 170,000 train-km
- Assumed 50% 3-carriage and 50% 4-carriage
- Downstream emission factors from Hobson et al. (2001) for Class 159 3-carriage:
    - CO_2: 3723 g/train-km
    - SO_2: 4.7 g/train-km
    - VOCs: 3.6 g/train-km
    - CO: 3.7 g/train-km
    - PM_{10}: 1.2 g/train-km
    - NO_x: 37.9 g/train-km

- Diesel consumption data from Hobson et al. (2001): 0.95 kg/train-km
- Assuming for 4-carriages the emissions and diesel consumption are $\times 4/3$
- Upstream emission factors from Chernyavs'ka and Gullí (2009) for diesel production, per kg of diesel:
    - CO_2e: 1312.5 g/kg
    - SO_x: 4.3 g/kg
    - VOCs: 0.8 g/kg
    - PM: 0.7 g/kg
    - NO_x: 4.1 g/kg

$$Annual\ downstream\ CO_2$$

$$= (50\% \times dist \times CO_2 factor) \quad + \left(50\% \times dist \times \tfrac{4}{3} CO_2 factor\right)$$

$$= \left(\tfrac{1}{2} \times 170{,}000\ km \times 3723\ g/km\right) + \left(\tfrac{1}{2} \times 170{,}000\ km \times \tfrac{4}{3} \times 3723\ g/km\right)$$

$$= 738{,}395{,}000\ g$$

$$Annual\ upstream\ CO_2$$

$$= (50\% \times dist \times fuel \times CO_2 factor) + \left(50\% \times dist \times \tfrac{4}{3} fuel \times CO_2 factor\right)$$

$$= \left(\tfrac{1}{2} \times 170{,}000\ km \times 0.95\ kg/km \times 1312.5\ g/kg\right)$$

$$+ \left(\tfrac{1}{2} \times 170{,}000\ km \times \tfrac{4}{3} \times 0.95\ kg/km \times 1312.5\ g/kg\right)$$

$$= 247{,}297{,}000\ g$$

$$Annual\ CO_2 = Annual\ downstream + Annual\ upstream$$

$$= 738{,}395{,}000\ g + 247{,}297{,}000\ g \approx 986\ tCO_2$$

The procedure for calculating emissions for electric rail followed those for calculating upstream diesel emissions, with Hobson et al. (2001) giving factors for electricity consumption in kWh/train-km, and using the low scenario factors from Hobson et al. (2001) and the Department for Business, Energy and Industrial Strategy and the Department for Environment, Farming and Rural Affairs (2019) for electricity grid emissions per kWh in the United Kingdom. The emissions were calculated for each pollutant by following the procedure outlined above, and this process was completed for each individual train class and on each individual line within Birmingham. Details can be found in Appendix 1, A1.1 and A1.2 for the travel distances and train class data, and Appendix 2, A2.1, A2.2. and A2.3 for the emission factors for diesel downstream, electricity, and diesel upstream.

Table 5.1 shows an example of a Diesel-Electric Multiple Unit (DEMU) and an Electric Multiple Unit (EMU) rolling stock classes found in Birmingham, with the calculated annual distance travelled, and the factors used to calculate emissions. The emissions are separated into those produced by diesel-fuelled rail and those produced by electric rail and summarised in Table 5.2. The analysis includes emissions from upstream fuel production and downstream at use. Though the upstream emissions do not affect the city directly in terms of localised impacts, they were counted as part of the city emissions because rail provides a service to the city. All emissions from electric rail are produced upstream, meaning electric rail does not produce localised at-use emissions. This makes electric rail less impactful from a local perspective, but not necessarily from a global perspective.

Table 5.1: Sample diesel and electric trains for Birmingham analysis (Hobson et al., 2001; BEIS and DEFRA, 2019; Chernyavs'ka and Gullí, 2009).

	Class 221 - Diesel (DEMU) 4 carriages		Class 323 - Electric (EMU) 3 carriages	
Annual distance travelled	411,000 km		995,000 km	
Fuel consumption	2.115 kg/train-km		9.10 kWh/train-km	
Emission factors	Upstream (g/kg diesel)	Downstream (g/train-km)	Upstream (g/train-km)	Downstream (g/train-km)
CO_2e/CO_2	1312.5	2594	1833	0
SO_2	4.3	3.3	2.1	0
VOCs	0.8	2.5	1.5	0
CO	/	8.2	0.3	0
PM_{10}	0.7	0.9	0.2	0
NO_x	4.1	26.8	2.5	0

/ refers to lack of data.

Table 5.2: Annual emissions from rail in Birmingham.

Pollutant (t/y)	Diesel Rail	Electric Rail	Annual Total
Annual distance travelled (train-km)	1,610,000	1,570,000	3,170,000
CO_2e/CO_2	6,970	4,320	11,300
SO_2	15.1	4.85	20.0
VOCs	6.87	3.54	10.4
CO	7.90	0.693	8.59
PM_{10}	3.29	0.385	3.68
NO_x	64.5	5.93	70.4

Whilst the distance travelled by diesel and electric rail within Birmingham is almost equal, diesel rail produces more of all the pollutants which are analysed. This demonstrates the difference in emissions production between diesel and electric rail, and the potential for emissions reduction. The charts in Figure 5.1 illustrate the share between diesel and electric rail for travel distance and each of the pollutants analysed. The comparative shares show that diesel produces around ten times more PM, NO_x and CO emissions than electric, all of which are the more harmful pollutants to human health.

Under the 2018 grid electricity mix, if all diesel trains were converted to electric, there would be a reduction in emissions of 52% for SO_2, 32% for VOC, 84% for CO, 79% for PM_{10} and 83% for NO_x. For carbon dioxide, this saving is lower at around 23%, which also shows that although the electricity grid produces less localised air pollutants, it still produces impactful pollutants at a global scale.

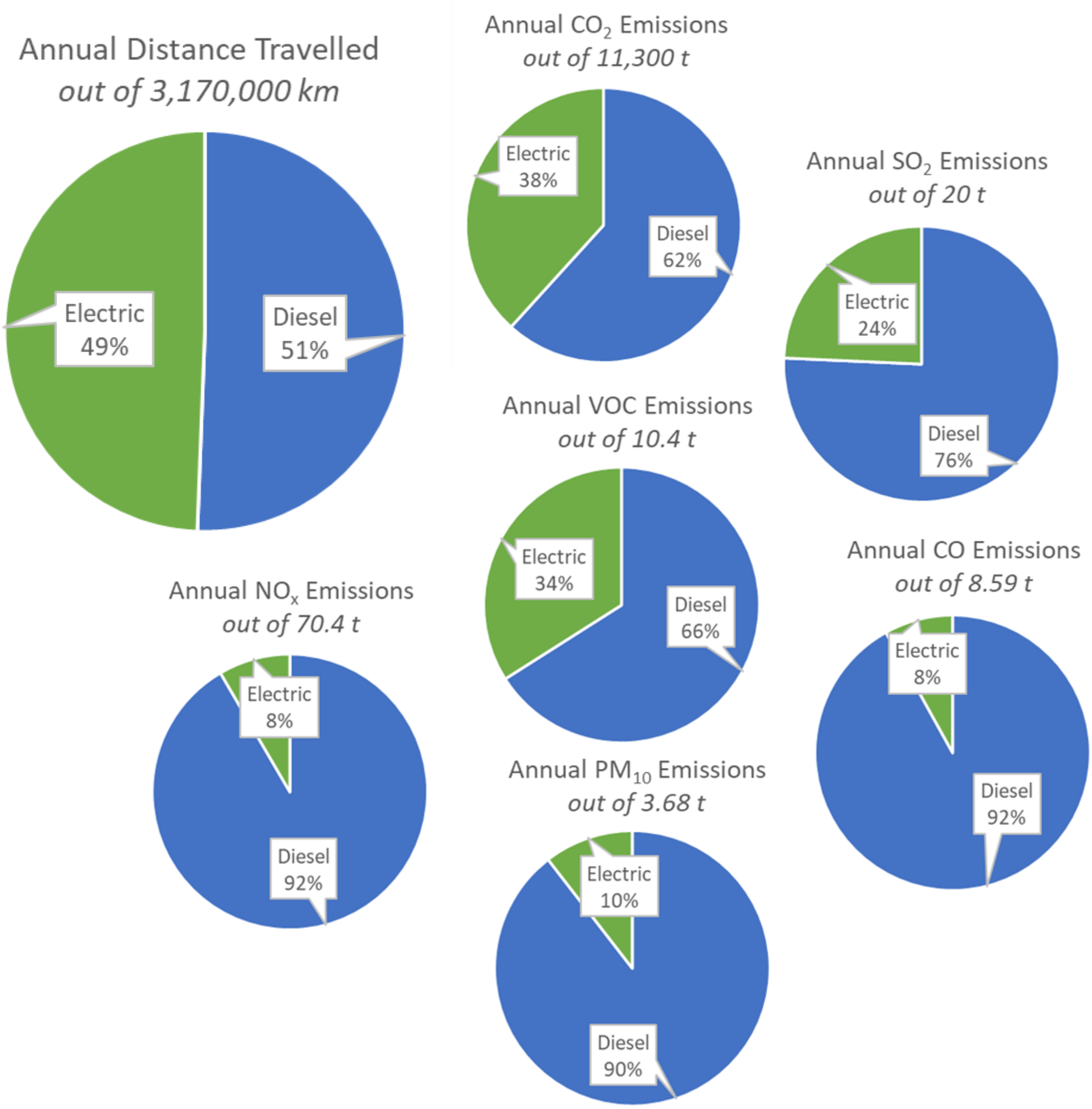

Figure 5.1: Shares of annual emissions between diesel and electric trains in Birmingham.

5.2.2. External Cost of Rail Emissions in Birmingham

Section 4.4.2 in Chapter 4 described the process used in this thesis to evaluate the external costs of rail traction emissions. To calculate the external costs using ExternE, the emissions summarised in Table 5.2 (except CO_2) were input to the online EcoSenseLE model, which gave the monetised results for localised health and environmental impacts. The full set of model results can be found in Appendix 3, A3.3. The Handbook on External Costs of Transport external cost analysis is based on travel distances for electric and diesel rail respectively, so the travel distances which are detailed in Appendix 1, A1.1, and summarised in Table 5.2 were multiplied by the external cost factors for HECT which were presented in Chapter 4, Section 4.4.2, and are summarised in Appendix A3.1. Global carbon dioxide costs were calculated using the CO_2 emissions values from Table 5.2, multiplied by the CO_2 costing factors detailed in Chapter 4, Section 4.4.2, and Appendix A3.4. The example calculation below shows the three external cost analysis procedures for diesel rail in Birmingham.

Example Calculation

For ExternE costs, the emissions which were calculated in Section 5.2.1 were input into the online model (Appendix 3, A3.2). The model then gave output monetisation of costs which are shown in detail in Appendix 3, A3.3. The output is given in 2010€, so these costs were converted to 2020£.

For HECT costs, the overall train-km travelled by train type shown in Table 5.2 was multiplied by the HECT factor (also in 2010€, Appendix 3, A3.1) as per equation 5.2:

- Passenger diesel, MU railcar, urban running: 204.5 €ct/train-km
- Passenger electric, MU railcar, urban running: 116.9 €ct/train-km

$$External\ costs\ from\ diesel = distance\ travelled \times HECT\ factor \qquad \dots(5.2)$$

$$= 1{,}610{,}000\ km \times 2.045\ €/km = 2010€\ 3{,}292{,}450$$

$$\approx 2020£\ 3{,}180{,}000$$

CO_2e costs were calculated by multiplying the CO_2e/CO_2 emissions, which were calculated in Section 5.2.1, by the cost factors from DfT (2021b) for 2020, as per equation 5.3:

- Low: 37.82 £/tCO_2e
- Central: 74.55 £/tCO_2e
- High: 112.37 £/tCO_2e

$$Monetisation\ of\ CO_2 = CO_2e\ emission \times CO_2e\ cost\ factor \qquad \dots(5.3)$$

$$Central\ CO_2e\ cost\ for\ 2020 = 6{,}970\ tCO_2/y \times 74.55\ £/tCO_2e = £\ 519{,}613.5$$

The results of the analysis of external costs over a year in Birmingham are summarised in Table 5.3. ExternE and HECT are two routes that have been used to analyse the same impact of emissions. Because the values vary quite significantly, the ExternE values are used to represent a lower potential cost, and the HECT values are used to represent a higher potential cost. The calculated values for CO_2 costs are also a range, and this is because there are low, central, and high values given for the cost of carbon. The total range of external costs given in Table 5.3 therefore expresses ExternE + minimum CO_2 cost as the lower end of the scale, and HECT + maximum CO_2 cost as the higher end of the scale. This measure is suitable to represent the range of external costs values, because ExternE and HECT analyse the same impacts but through two different routes.

Table 5.3: Annual external costs for Birmingham rail emissions.

Monetisation (£)	Diesel Rail	Electric Rail	Total
ExternE	766,000	110,000	876,000
HECT	3,180,000	1,770,000	4,950,000
CO_2e	264,000 - 783,000	164,000 - 486,000	427,000 - 1,270,000
Total Range	1,030,000 - 3,960,000	274,000 - 2,260,000	1,300,000 - 6,220,000

Externalities from rail traction are costing Birmingham between approximately 1.3 and 6.2 million pounds annually. If all diesel rail were converted to electric, this would reduce the external costs by around 27% to 58% (£750k to £1.7M), depending on the method used for estimating external costs and considering the reduction in emissions from diesel and subsequent increase in emissions from electricity. As expected, due to the different methods for estimating external costs, the values given by HECT and ExternE are quite different. The values also show that HECT and ExternE results assign different relative shares of results between diesel and electric rail. This is illustrated in Figure 5.3, which shows the shares of the total cost assigned to diesel and electric rail, respectively. In this diagram, the central result for CO_2e costing is used. The diesel/electric share of CO_2e costs is the same as the share of CO_2e emissions, which is expected as the CO_2e emissions values are monetised using the same cost factors. The different shares of the total emissions between ExternE and HECT demonstrated in Figure 5.2, show that HECT assigns a significantly higher external cost to electric rail relative to diesel. This is likely due to the fact that HECT uses data from 2010, whereas since 2010, the emissions intensity from the UK electricity grid has reduced by 50% (BEIS, 2020a).

ExternE follows a bottom-up approach, whereby the emissions were calculated from primary data and input into the impact and monetisation calculator. This means the external cost values are calculated based on the specific emission factors for train classes and carriage numbers, and that the electric rail factors are based on the UK electricity grid in 2018. HECT on the other hand, follows a top-down approach, where the train distance travelled is input into the calculator. This method means there is less accuracy and no accounting for different train types or number of carriages, whereas ExternE can account for these in the emissions evaluation. The HECT results are more dominated by the assumptions within the methodology, and the values given, for example, for UK electricity emissions intensity. The next section moves in to the analysis of emissions for the three case studies, in order to compare between rail traction options. It may become relevant to note the discrepancy in external costs for electric rail calculated using HECT.

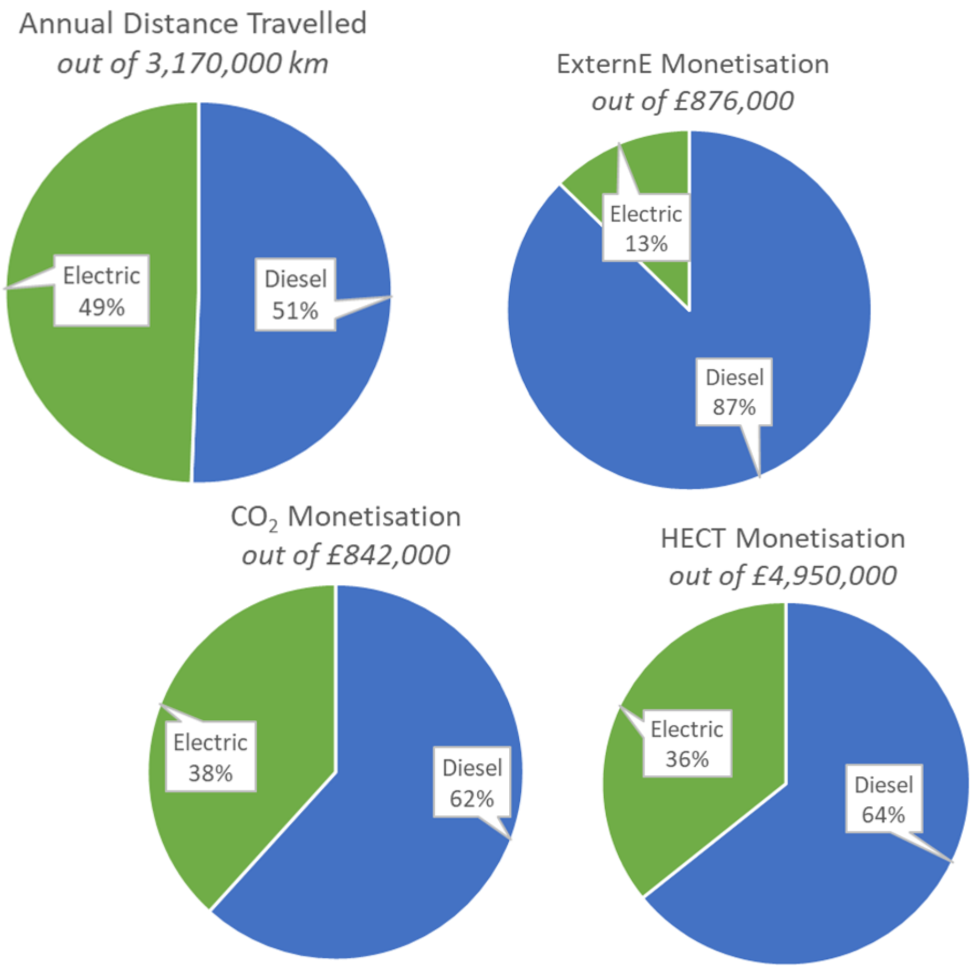

Figure 5.2: Shares of annual external costs between diesel and electric trains in Birmingham.

5.3. Comparison of Rail Traction Technologies

5.3.1. Case Study Emissions Analysis

This section contains the first step towards comparing between options for rail traction, and the first step towards exploring the external costs for these technologies. This section addresses the aim of evaluating the emissions from rail, with the current technology (diesel), and the options for decarbonisation (electric and fuel cell). Within fuel cell rail, there is also a comparison of seven different sources of hydrogen production, defined in Chapter 4, Section 4.4.1, as:

- Imported hydrogen produced from steam methane reforming (SMR)
- Imported hydrogen produced from electrolysis with European Union average grid electricity
- Onsite production via steam methane reforming, with UK gas grid methane
- Onsite production via electrolysis, with UK grid electricity
- Onsite production via electrolysis, with solar power
- Onsite production via electrolysis, with onshore wind power
- Onsite production via electrolysis, with offshore wind power

The emission values for imported hydrogen produced at centralised industrial scales include an assumed value for transport (although this is not accurately based on the distance), which illustrates the greater emissions intensity of centralised production methods with transport requirements. The emissions intensity of the grid is expected to reduce over time, as would benefit electric rail, however this is taken as a snapshot of the current situation to analyse low-carbon technologies in 2020. The emissions were calculated following the procedure detailed in Chapter 4, Section 4.4.1. The emissions for diesel rail encompass the upstream emissions from fuel production and the at-use downstream emissions. The emissions for electric and fuel cell rail are from electricity or hydrogen production stages respectively. In contrast to the evaluation for Birmingham city centre, the results given for the three case studies are on a 30-year lifetime basis. An example calculation below shows the process for calculating the NO_x emissions from hydrogen produced offsite via SMR. The emissions analysis was based on travel distance data and fuel consumption data, which are detailed in Appendix 1. A selection of emission factors for diesel and electric rail was presented in Table 5.1, and Table 5.4 shows the emission factors used to evaluate hydrogen production. Detail of the emission factors can be found in Appendix 2, and detail of how the travel distances were calculated can be found in Appendix 1, A1.1, based on the method described in Chapter 4, Section 4.2.5.

Example Calculation

The emissions from diesel and electric rail were calculated following the procedure which was outlined in Section 5.2.1 for Birmingham, using emissions data for the train class which undertakes the case study route, or would be an estimated equivalent replacement where the data is not available (Appendix 2, A2.1).

The emissions for fuel cell rail were calculated similarly to the upstream diesel emissions. These were calculated using the emission factors detailed in Appendix 2, A2.3 given in g/kgH_2, and the estimated hydrogen consumption based on hydrogen consumption factors and the annual distance travelled (Appendix 1, A1.1 and A1.2). For example, NO_x emissions from hydrogen produced via SMR for the regional case study:

- Annual distance travelled: 3,829,990 km

- In order to provide the current capacity level, assuming 40% of fuel cell trains are run as double, which doubles the consumption
- Hydrogen consumption rate (Navas, 2017): 0.3 kgH_2/train-km (per train)
- NO_x emissions for hydrogen SMR (Chernyavs'ka and Gullí, 2009): 24 g/kgH_2

$$Annual\ hydrogen\ consumption = distance \times 140\% \times consumption\ rate$$

$$= 3{,}829{,}990\ km \times 1.4 \times 0.3\ kgH_2/km = 1{,}608{,}600\ kgH_2$$

$$Hydrogen\ SMR\ NO_x\ emissions = hydrogen \times emission\ factor$$

$$= 1{,}608{,}600\ kgH_2 \times 24\ gNO_x/kgH_2 \approx 38{,}600\ kgNO_x$$

$$Lifetime\ NO_x\ emissions = Annual\ emissions \times 30$$

$$= 38{,}600\ kgNO_x \times 30 \approx 1{,}160\ tNO_x$$

Table 5.4: Emission factors for hydrogen production ([1]Chernyavs'ka and Gullí, 2009; [2]Hobson et al., 2001, [3]Navas, 2017; [4]BEIS and DEFRA, 2019).

Emission Factors (g/kg H_2)	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Offsite[1]	Onsite	Offsite (EU grid)[1]	Onsite (UK grid)[2]
CO_2e	/	/	23208	/
CO_2	2300[3]	1345	/	13440[4]
NO_x	24	15.6	30.5	19.7
SO_x	21.6	2.1	71	6.7
PM	4.2	1.25	7.2	2.18
CO	/	/	/	4.3
VOC	2.6	1.5	2.5	1.44

CO_2e includes CO_2, CH_4, and N_2O.
Onsite factors for SMR were estimated assuming a same relative difference as between the on and offsite electrolysis data.
/ refers to a lack of data.

Table 5.5 displays the results of the emissions analysis for the first case study, the regional route. For this route, the annual travel distance calculated is 3,830,000 km (Appendix 1, Table A1.2). The emissions were calculated on this distance basis, for each traction technology option, and then multiplied by 30 to give the results on a 30-year lifetime basis. Within Table 5.5, the results for fuel cell rail have been split into two groups depending on whether the hydrogen is from imported sources or produced onsite. Table 5.6 details the emissions from hydrogen production options, keeping in consideration that hydrogen produced from renewable sources produces no emissions.

Table 5.5: Emissions analysis over 30 years, regional case study.

Emissions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
CO_2e/CO_2 (t)	436,000	212,000	264,000 - 1,120,000	0 - 655,000
SO_2 (t)	931	106	1,040 - 3,430	0 - 327
VOCs (t)	433	22.6	122 - 125	0 - 72.2
CO (t)	352	67.9	/	0 - /
PM_{10} (t)	204	33.9	201 - 349	0 -105
NO_x (t)	4,040	309	1,160 - 1,470	0 - 956

/ refers to a lack of data.

Table 5.6: Hydrogen production emissions over 30 years, regional case study.

Emissions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
CO_2e/CO_2 (t)	264,000	155,000	1,120,000	655,000
SO_x (t)	1,040	99.6	3,430	327
VOC (t)	125	72.2	122	70
CO (t)	/	/	/	210
PM (t)	201	60.5	349	105
NO_x (t)	1,160	752	1,470	956

/ refers to a lack of data.

Values for CO were not always available, meaning there is a lack of data which unfortunately defaults the values to zero, when in reality they may be significant pollutants. The decision was made to not try to estimate these values, which would obscure the fact that these values are not recorded. It is vital that to reduce pollution, the pollution needs to be recorded, and this is a significant omission from the data. The emissions from electric rail are consistently lower than for diesel rail, and the emissions comparison for fuel cell rail depends on the source of hydrogen. Using imported hydrogen produces significantly more emissions in all categories except VOCs and NO_x, which are lower than diesel but higher than electric. Onsite hydrogen production can emit lower emissions than diesel in general, except for CO_2 emissions when hydrogen is produced via electrolysis using grid electricity. The traction technologies which produce the greatest emissions in this case study are diesel, fuel cell with imported hydrogen, and fuel cell with onsite production of hydrogen with electrolysis using grid electricity. The traction options which produce the lowest emissions are fuel cell with hydrogen produced via electrolysis using renewable electricity and electric rail.

A comparison between emissions is illustrated in Figure 5.3. This graph represents a comparison of the emissions from rail traction options, relative to each other. The emission values have been standardised by dividing the value for emission produced by each technology option by the highest value for each pollutant. The greater the relative amount of emissions caused by a technology option, the further towards the outer edge of the diagram the resulting point. The centre of the graph is a blue dot, which represents the zero-emission option using renewable electricity. Each type of pollutant is represented by an axis, and each traction technology option is represented by a different colour dot and line. Where data was unavailable for CO, the value has been assumed as the average 0.5. The following abbreviations are used to refer to the different hydrogen production methods in graphical representations:

- SMR imp H2 - Imported hydrogen produced from steam methane reforming

- Elec imp H2 - Imported hydrogen produced from electrolysis with EU average grid electricity
- SMR ons H2 - Onsite production via steam methane reforming, with imported methane
- Elec ons H2 - Onsite production via electrolysis, with imported UK grid electricity
- REN H2 - Onsite production via electrolysis, with onsite renewable power

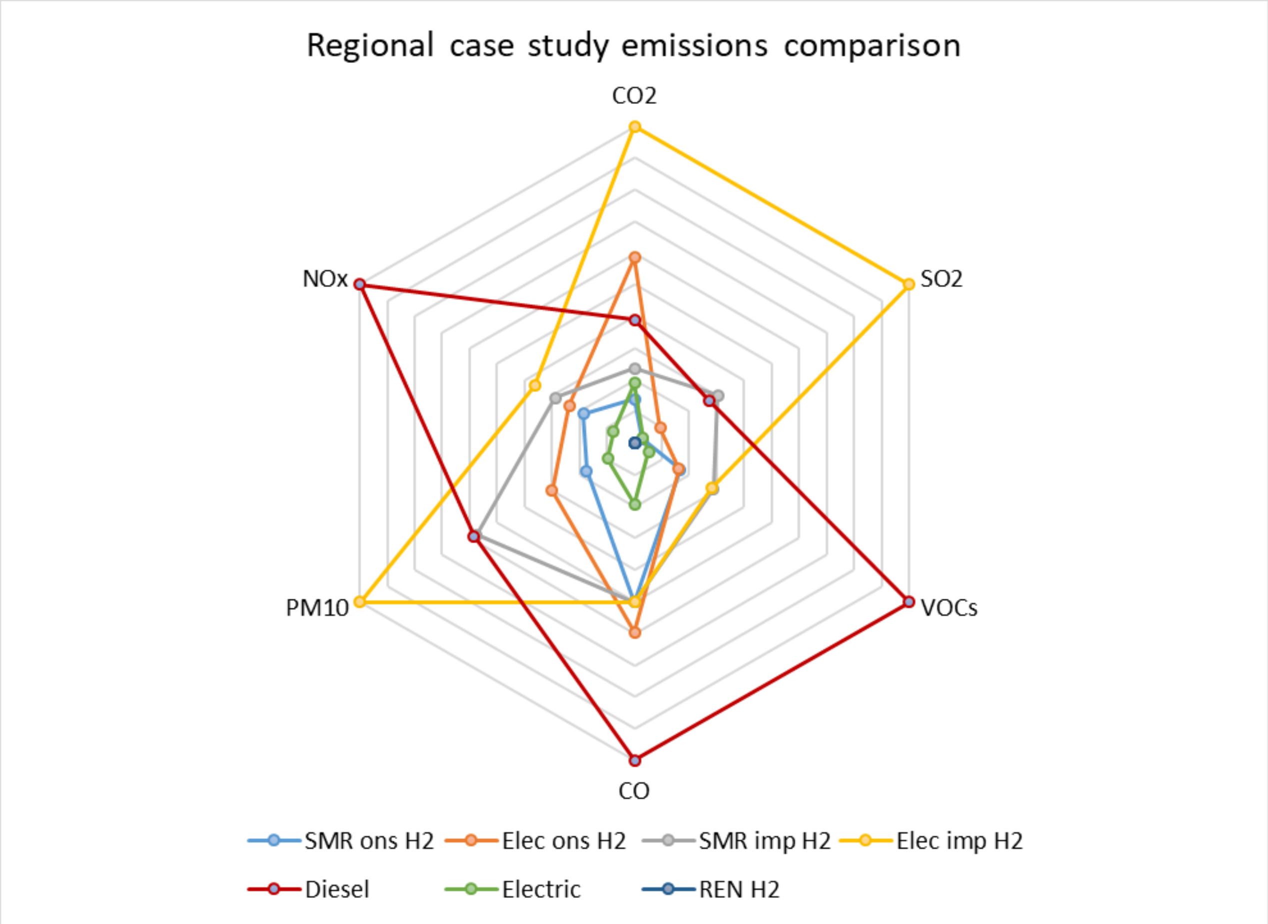

Figure 5.3: Comparison of standardised emissions, regional case study.
Please note: The values for CO for SMR ons H2, SMR imp H2, and Elec imp H2 are represented as 0.5 on the diagram because the data was unavailable.

The process for calculating emissions was repeated for the long-distance case study, and the results are summarised in Tables 5.7 and 5.8. The annual distance travelled for the long-distance case study is 10,401,731 km. The comparison of emissions produced by different traction options is similar to the findings for the regional case study. However, this route requires different fuel cell trains which have a greater fuel consumption, due to the longer distances and faster speeds required. As this technology is not as developed as fuel cell rail for shorter journeys (meaning the iLint), current status means this route requires exponentially more hydrogen to provide the services. As a result, although the options which create the least emissions are still fuel cell rail with renewably produced hydrogen and electric rail, the option of fuel cell rail with imported hydrogen, and hydrogen produced from electrolysis with grid electricity, perform comparatively worse on the basis of emissions production. Diesel rail produces less emissions than the option using imported hydrogen from EU average grid electricity. This reflects the lower efficiency of the less-developed fuel cell locomotive technology. The comparison of emissions is illustrated in Figure 5.4.

Table 5.7: Emissions analysis over 30 years, long-distance case study.

Emissions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
CO_2e/CO_2 (t)	1,870,000	1,580,000	718,000 - 9,510,000	0 - 5,560,000
SO_2 (t)	5,390	787	8,870 - 29,100	0 - 2,770
VOCs (t)	1,880	169	1,030 - 1,060	0 - 613
CO (t)	3,920	506	/	0 - 1,780
PM_{10} (t)	1,130	253	1,710 - 2,970	0 - 891
NO_x (t)	16,400	2,310	9,840 - 12,500	0 - 8,120

/ refers to a lack of data.

Table 5.8: Hydrogen production emissions over 30 years, long-distance case study.

Emissions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
CO_2e/CO_2 (t)	718,000	420,000	9,510,000	5,560,000
SO_x (t)	8,870	845	29,100	2,770
VOC (t)	1,060	613	1,030	594
CO (t)	/	/	/	1,780
PM (t)	1,710	514	2,970	891
NO_x (t)	9,840	6,380	12,500	8,120

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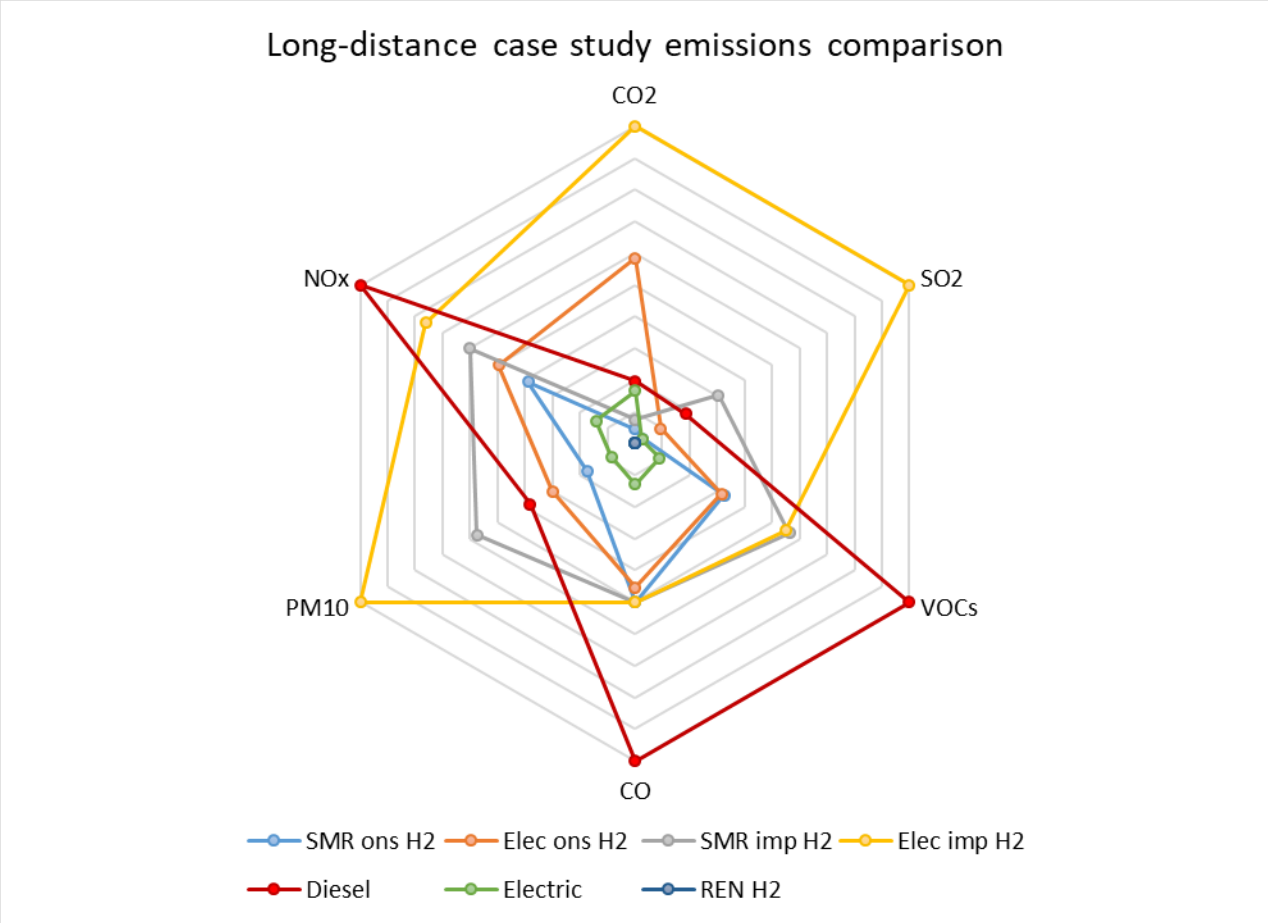

Figure 5.4: Comparison of standardised emissions, long-distance case study.
Please note: The values for CO for SMR ons H2, SMR imp H2, and Elec imp H2 are represented as 0.5 on the diagram because the data was unavailable.

The emissions were calculated for the rural case study following the same procedure, and the results are displayed in Tables 5.9 and 5.10. The annual distance travelled calculated for the rural case study is 2,302,680 km. The comparison of emissions between traction options is again similar to that for the regional case study, in that the traction technologies which produce the greatest emissions are diesel, fuel cell with imported hydrogen, and fuel cell with onsite production of hydrogen with electrolysis using grid electricity. Likewise, the traction option which produces the lowest emissions is fuel cell with hydrogen produced via electrolysis using renewable electricity. However, due to the lower service use and hence lower hydrogen requirements, electric rail produces slightly more emissions that the next lowest emitting hydrogen source, which is hydrogen produced from onsite SMR. The comparison of emissions is illustrated in Figure 5.5. The next section evaluates the impact of these calculated emissions through external cost analysis.

Table 5.9: Emissions analysis over 30 years, rural case study.

Emissions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
CO_2e/CO_2 (t)	239,000	188,000	159,000 - 481,000	0 - 281,000
SO_2 (t)	515	94	448 - 1,470	0 - 140
VOCs (t)	235	20.1	52.2 - 53.8	0 - 31
CO (t)	193	60.3	/	0 - 90.1
PM_{10} (t)	110	30.1	86.4 - 150	0 - 45.1
NO_x (t)	2,210	275	497 - 633	0 - 411

/ refers to a lack of data.

Table 5.10: Hydrogen production emissions over 30 years, rural case study.

Emissions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
CO_2e/CO_2 (t)	159,000	92,900	481,000	281,000
SO_x (t)	448	42.8	1,470	140
VOC (t)	53.8	31.0	52.2	30.0
CO (t)	/	/	/	90.1
PM (t)	86.4	26.0	150	45.1
NO_x (t)	497	323	633	411

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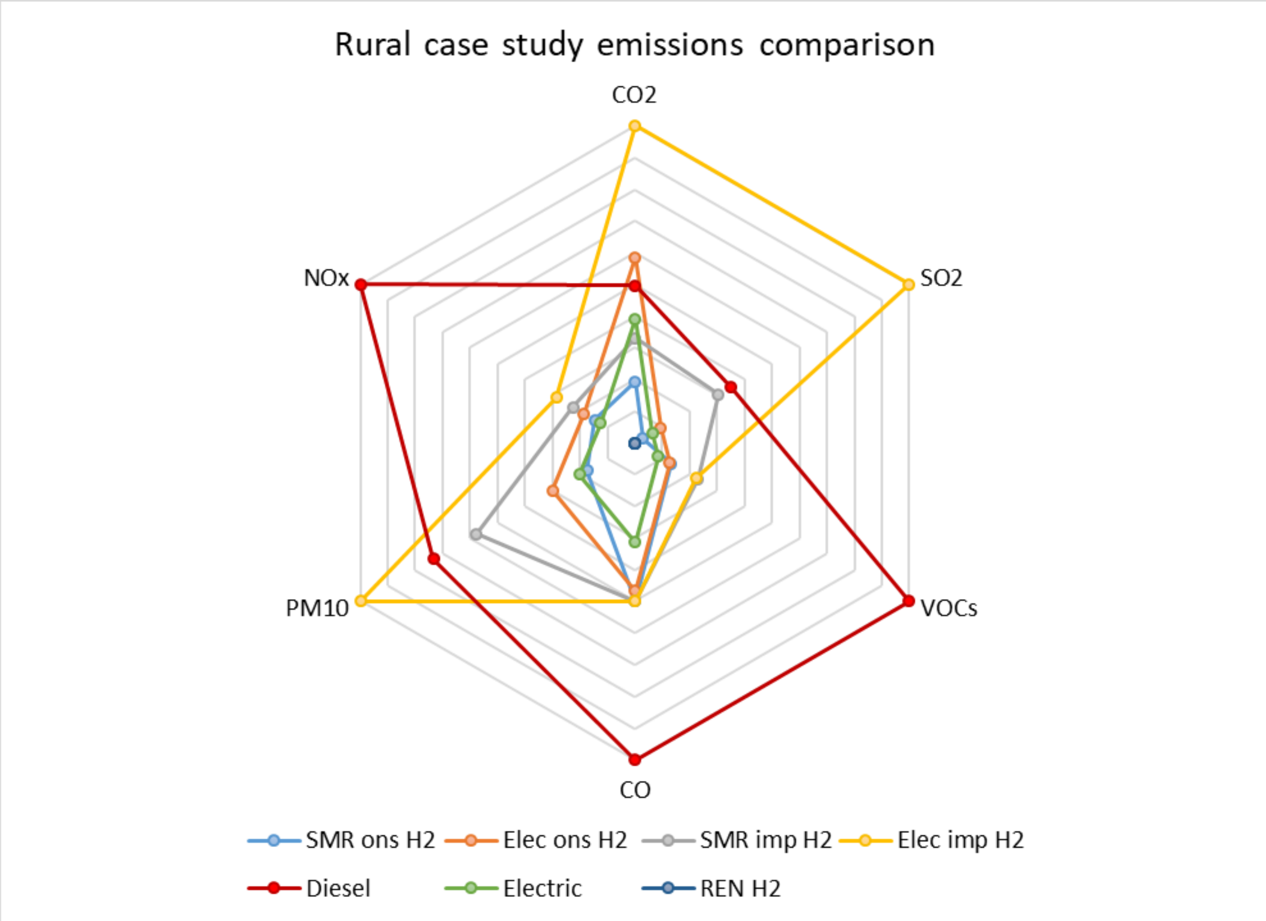

Figure 5.5: Comparison of standardised emissions, rural case study.
Please note: The values for CO for SMR ons H2, SMR imp H2, and Elec imp H2 are represented as 0.5 on the diagram because the data was unavailable.

5.3.2. Case Study External Cost Analysis

This section reports the results of the external cost analysis, which follows the research objective of evaluating the impact of emissions through external cost analysis, for the current train technology (diesel) and replacement technologies for decarbonisation (electric and fuel cell). This progression allows an exploration of the external costs of British rail. The process followed to evaluate the external costs of rail traction emissions was detailed in Section 4.4.2 in Chapter 4, and an example calculation shown in Section 5.2.2. To calculate the external costs using the ExternE methodology, the emissions which were presented in the previous section, in Tables 5.5 to 5.10, were input to the online EcoSenseLE model (except CO_2). This model then gave the monetised results for localised health and environmental impacts. The full set of model results, for each technology option and each case study, can be found in Appendix 3, A3.3. The HECT external cost analysis is based on travel distances, but only contains data for electric and diesel rail. To calculate HECT external costs for electric and diesel, the travel distances, which are detailed in Appendix 1, A1.1, were multiplied by the external cost factors for HECT in Appendix 3, A3.1. Global carbon dioxide costs were calculated using the CO_2 emissions values from Tables 5.5 to 5.10, multiplied by the CO_2e costing factors from DfT.

Akin to the emission analysis, the external cost calculations were based on the 30-year lifetime. The results of the external cost analysis are presented in Tables 5.11, 5.13, and 5.15 for regional, long-distance, and rural case studies respectively. As with the emissions analysis, the external costs include emissions from downstream at-use, and upstream fuel production. The fuel cell options have also again been split into imported hydrogen and onsite hydrogen, with details separated into Tables 5.12, 5.14 and 5.16. Hydrogen produced from renewable electricity has no associated external costs, and CO_2e costs have a low-central-high cost range (DfT, 2021b).

Due to the fact that the HECT methodology does not include data for fuel cell rail, and gives significantly higher values for external costs than ExternE, the calculated total external cost range cannot include HECT monetisation, to provide a fair means of comparison. This means HECT data is also not included in graphical comparisons of the external costs in the remainder of this section.

Table 5.11: External costs over 30 years, regional case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
ExternE	54.6	4.66	33.4 - 76.1	0 - 14.4
HECT	227	130	/	/
CO_2e	31.6 - 94.7	15.3 - 46	19.1 - 243	0 - 142
Total (ExternE + CO_2e)	86.2 - 149	20 - 50.7	52.5 - 319	0 - 156

/ refers to a lack of data.

Table 5.12: External costs of hydrogen production over 30 years, regional case study.

£millions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
ExternE	33.4	9.42	76.1	14.4
CO_2e	19.1 - 57.4	11.2 - 33.6	81 - 243	47.4 - 142
Total (ExternE + CO_2e)	52.5 - 90.8	20.6 - 43	157 - 319	61.8 - 156

Table 5.13: External costs over 30 years, long-distance case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
ExternE	209	30.9	262 - 616	0 - 109
HECT	511	135	/	/
CO_2e	135 - 405	114 - 343	51.9 - 2,060	0 - 1,210
Total (ExternE + CO_2e)	344 - 614	145 - 374	314 - 2,670	0 - 1,320

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Table 5.14: External costs of hydrogen production over 30 years, long-distance case study.

£millions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
ExternE	262	69.0	616	109
CO_2e	51.9 - 156	30.4 - 91.1	688 - 2,060	402 - 1,210
Total (ExternE + CO_2e)	314 - 418	99.4 - 160	1,300 - 2,670	511 - 1,320

Table 5.15: External costs over 30 years, rural case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
ExternE	25.7	3.61	13.1 - 30.9	0 - 5.40
HECT	61.3	20.1	/	/
CO_2e	17.4 - 51.9	13.6 - 40.8	11.5 - 104	0 - 61
Total (ExternE + CO_2e)	43.1 - 77.6	17.2 - 44.4	24.6 - 135	0 - 66.5

/ refers to a lack of data.

Table 5.16: External costs of hydrogen production over 30 years, rural case study.

£millions	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
	Imported	Onsite	Imported (EU grid)	Onsite (UK grid)
ExternE	13.1	3.42	30.9	5.40
CO_2e	11.5 - 34.5	6.72 - 20.2	34.8 - 104	20.3 - 61.1
Total (ExternE + CO_2e)	24.6 - 47.6	10.1 - 23.6	65.7 - 135	25.7 - 66.5

As with the emissions analysis, the comparison between rail options is very similar for all three case studies. This analysis shows that overall, electric trains are lower in external costs than diesel. Fuel cell rail provides the potential to reduce external costs further, if the hydrogen is produced from renewable sources - but it can also lead to higher external costs if the hydrogen is sourced from highly polluting processes. This highlights the necessity for a more whole life approach to emissions analysis: at point of use, fuel cell and electric produce no emissions, which in itself can be beneficial (for example to reduce air pollution in cities). However, moving to a broader perspective entails considering emissions produced in the fuel production cycle, and in this case fuel cell rail can be more damaging at a global scale, if implemented without thought to the source of hydrogen used. To aid the comparison of rail traction options based on external costs, Figures 5.6, 5.7 and 5.8 illustrate the average of the total ExternE+CO_2 external costs from

Tables 5.11 to 5.16 above, broken down into the sources of emissions (whether upstream or downstream).

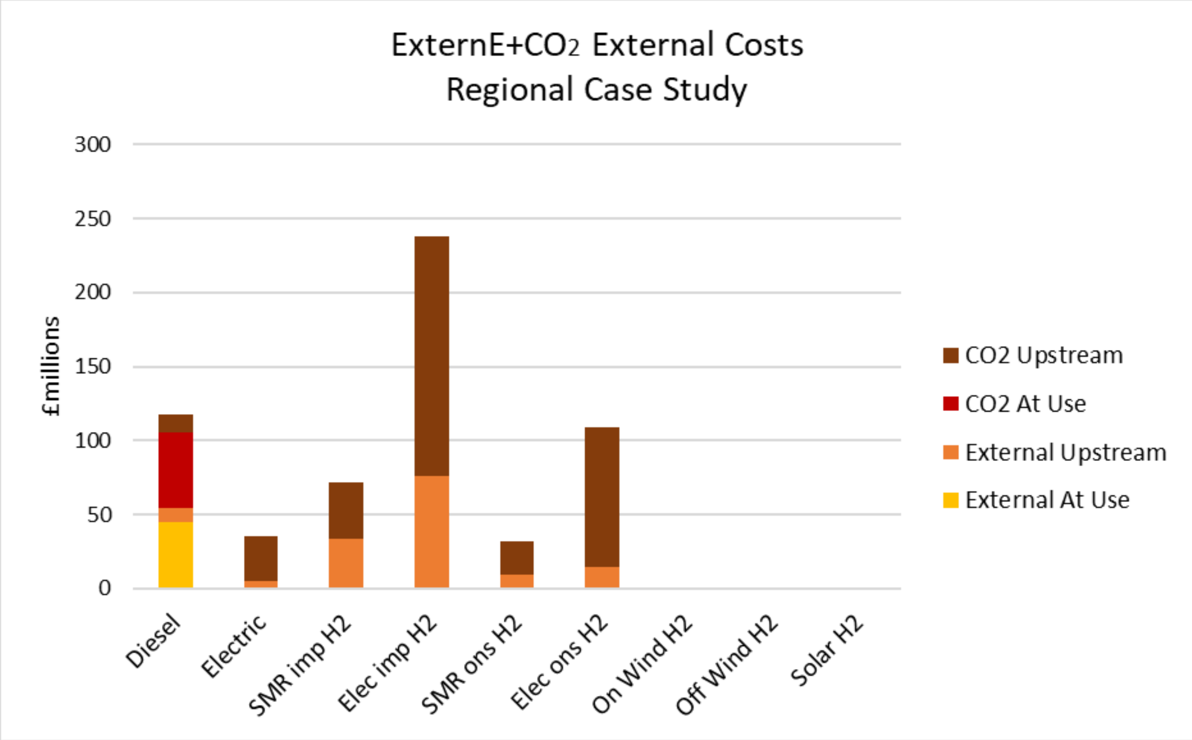

Figure 5.6: Breakdown of external costs, regional case study.

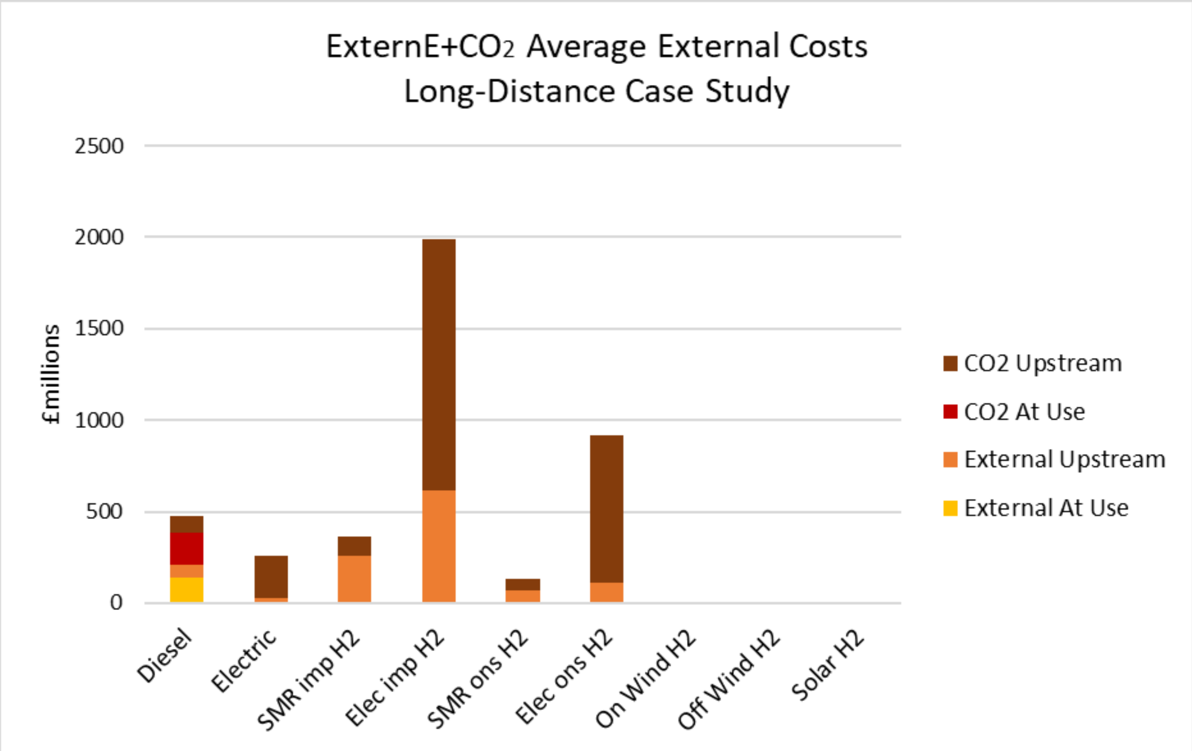

Figure 5.7: Breakdown of external costs, long-distance case study.

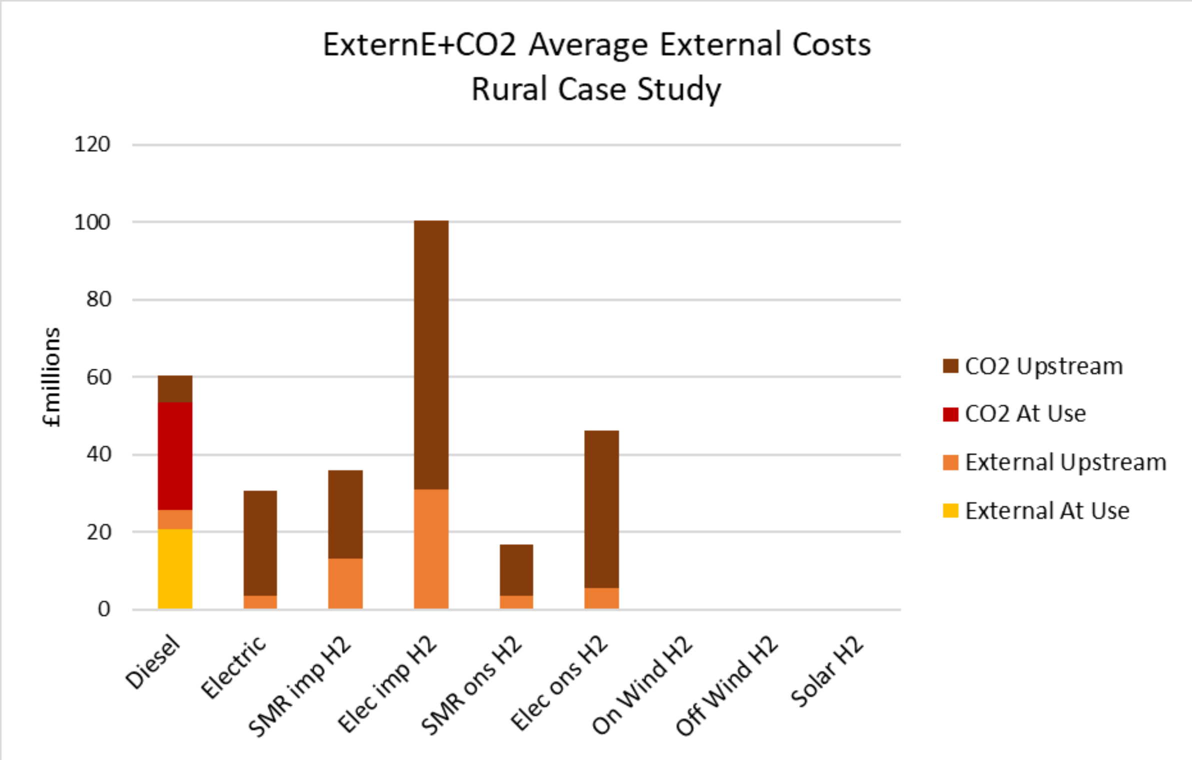

Figure 5.8: Breakdown of external costs, rural case study.

These graphs show that, consistently across case studies, the options which produce the lowest external costs, are fuel cell rail with hydrogen produced onsite via electrolysis with renewable energy, and onsite via SMR. These hydrogen rail options are then followed by electric rail, then hydrogen from centralised, offsite SMR. Diesel rail and hydrogen from grid electrolysis are the worst-performing in terms of external costs. Diesel external costs are comparatively higher for the regional case study, which is expected from the route with a higher proportion of urban running, meaning health impacts from local air pollution are more pronounced. Diesel costs are also comparatively higher for the rural route, which could be due to the improved efficiency of fuel cells and the reduction in fuel requirements. These graphs show that global CO_2e costs have a higher share of external costs than localised air pollution costs for all options which do not produce tailpipe emissions, but is about equal share of external costs for diesel.

Treatment of Uncertainty

External cost analysis is an inherently uncertain science, due to the fact that it involves placing cost values on assets which are not included in normal market-pricing. Figures 5.9, 5.10 and 5.11 illustrate the average external costs as shown above, but with an error bar representing the range of external cost values shown in Tables 5.11 to 5.16. The error bars are calculated from the standard deviation from the average values. The error represents the minimum to maximum range of values within which the 'real' external cost would be expected. Important to note, that for these error bars, the uncertainty for each traction method comes from the same sources. This means that if the 'real' result were to be the minimum value within each error, that result would be minimum for all traction options. It would not be possible to, for example, have the maximum value for electric rail but the minimum value for diesel. Thus, although the high uncertainty means there is a large amount of crossover between options, the relative impact from emissions remains the same, regardless of the uncertainty. This shows the value of external costing analysis as a means of comparing the impacts of options to fulfil the same function, even if the absolute values come with high uncertainty.

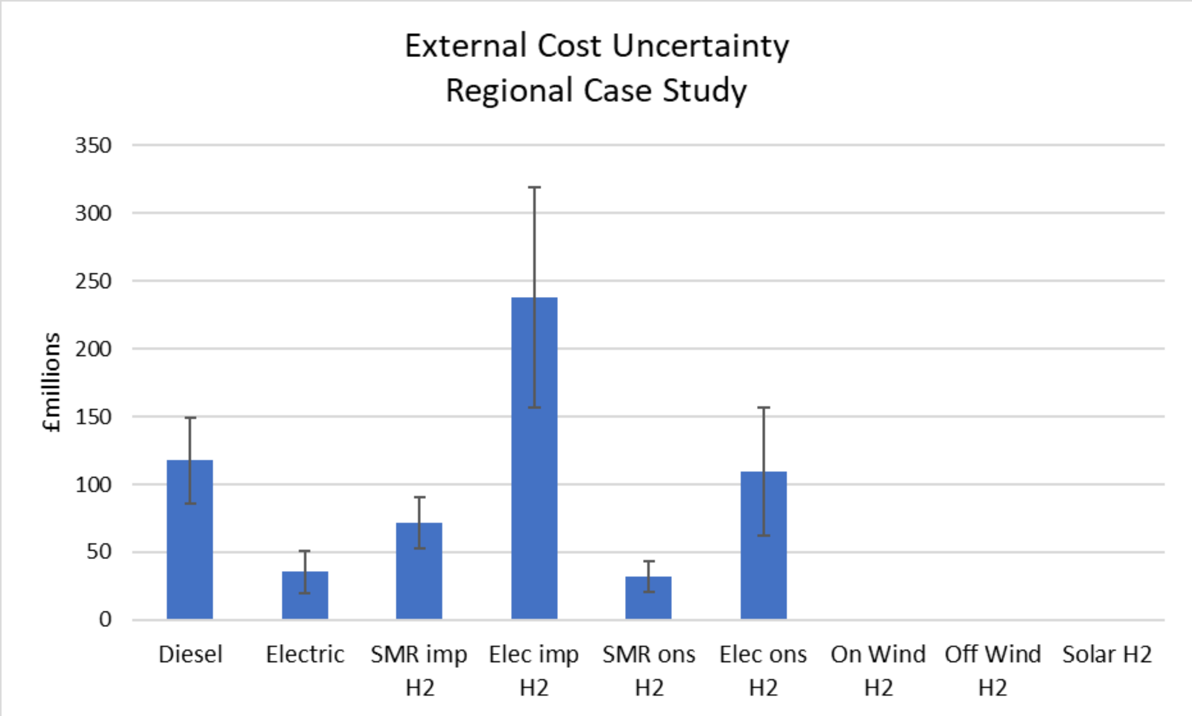

Figure 5.9: External cost range, regional case study.

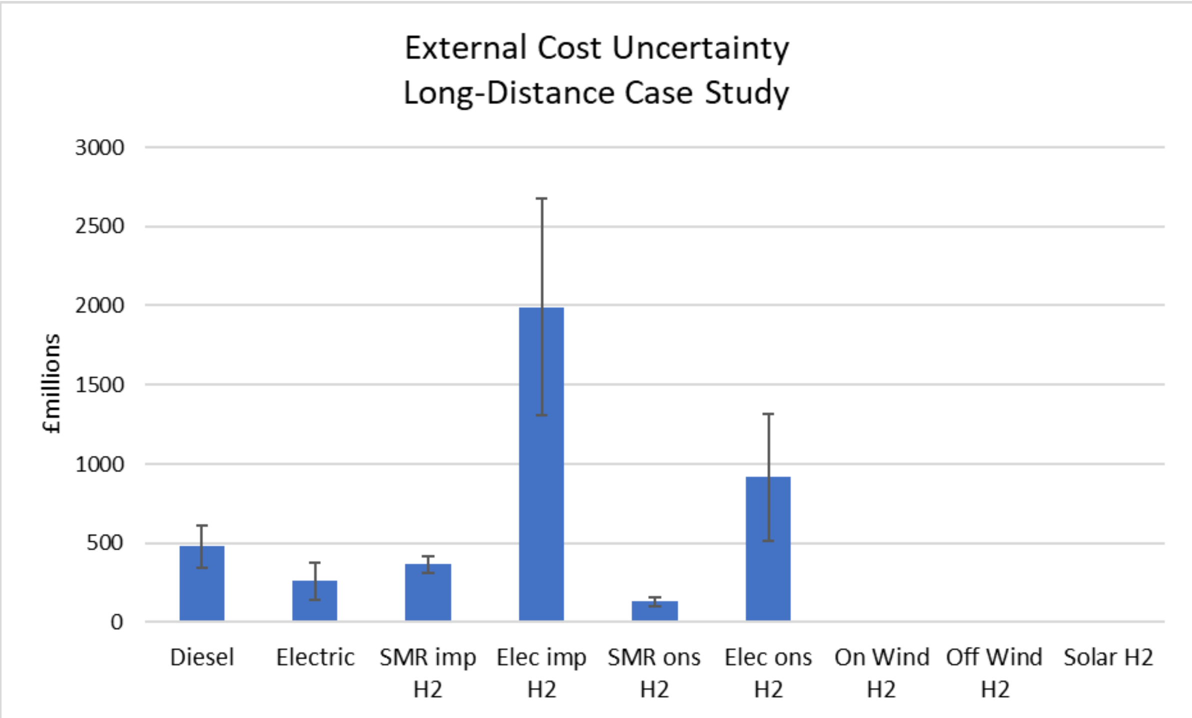

Figure 5.10: External cost range, long-distance case study.

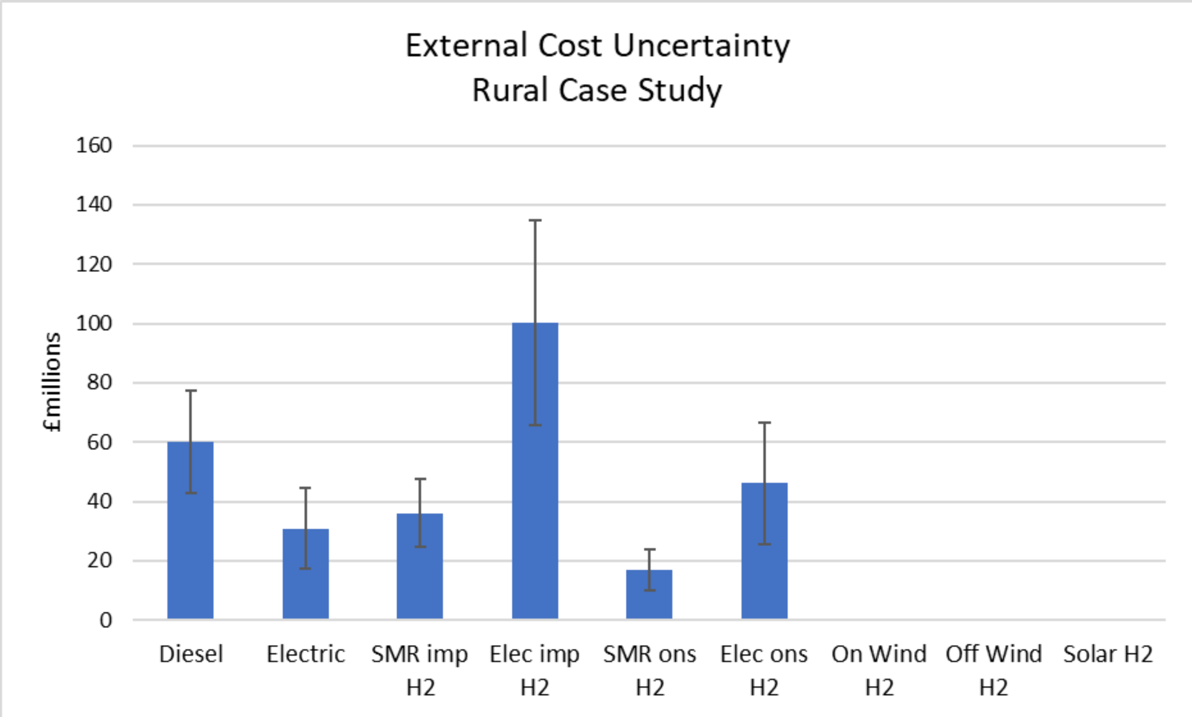

Figure 5.11: External cost range, rural case study.

A lack of updated data affects the evaluation of external costs. The EcoSenseLE model to evaluate ExternE costs was last updated in 2017, however it is uncertain whether at that time the values on which the model is based were updated, so these results could also be out of date (IER, 2017). Emissions-related data changes rapidly, and as the impacts of climate change grow, cost values for environmental and social damage could be expected to grow. Perhaps an updated methodology for evaluating external costs could be created, using more up to date figures for emissions intensity of activities (such as the electricity grid, and varying ages of diesel engines), as well as more up to date monetisation values, based on the social and environmental impacts of climate change that we are already seeing. Updated emissions values could be expected to be lower, as efforts to improve efficiency and reduce emissions intensity are made. However, the monetisation of impacts would be expected to lead to higher values, as negative impacts are growing and worsening as opportunities to reduce climate change impacts are missed.

Despite the significant uncertainties involved in external cost analysis, it remains a useful tool to attempt to include the value of non-market goods into pricing, and to showcase the fact that there are impacts which are not included in market pricing.

5.4. External Costs Discussion

The previous section illustrated, through representation of the range of values produced in the analysis, that external cost evaluation is not an exact science. The results are dependent on the choice of methodology and input parameters, as the difference in results between ExternE and HECT analysis demonstrates. Although these two methods have been treated as giving minimum and maximum values, it is likely that a different monetisation method would give yet different results. Although the external costs evaluated are subject to uncertainty, they provide a means to compare between the options for rail traction, and enable the inclusion of sustainability considerations into the evaluation of the Overall Costs for rail. The potential greatest strength of external cost evaluation is in opening the conversations around sustainable development, through an easily understood medium. This section discusses how externalities can be used as a measure of unsustainability, the implications of externality internalisation for British rail, and the consideration of local and global impacts.

5.4.1. Externalities as a Measure of Unsustainability

The evaluation of externalities is a method of demonstrating and including environmental and social sustainability issues into cost-based decision-making. Although monetisation of non-market goods is subject to uncertainty, it gives consideration to aspects which would otherwise be ignored. The issue arises in that there is no defined, standard, objective way of assigning monetary value (Cairns, 2007). There is an argument to say that sustainability decisions should ideally be based on other factors than money (Bebbington et al,. 2006), and some things perhaps should not be monetised (Unerman et al., 2018). However, there is also the understanding that monetisation of non-market goods is a necessary means to a sustainable accounting end. Without some inclusion of environmental or social issues into market values, decisions become based on incomplete information, which leads to the misallocation of resources, and environmental and social damage (Lamberton, 2005). Money is an easily understood concept by business, politics, and non-experts - although it is critical to stress than monetisation can be complex, and based on subjective data. Assuming monetisation values are 'fact' creates the potential to mislead (Krewitt, 2002; Herbohn, 2005; Gasparatos et al., 2007; Unerman et al., 2018).

In this research, the monetisation of external costs is done for two purposes: to provide a means of defining the current impact of rail emissions in Birmingham, and to enable the inclusion of emissions impact into an exploration and comparison of costs of rail traction options. Emissions have been monetised using two analysis methodologies, both of which use Willingness to Pay (Chapter 3, 3.4.3) to assign monetary values to localised impacts to human health and the environment. Externality evaluation is likely to not include enough data to show the absolute sustainability of a process, but it enables a comparison between multiple options based on their relative unsustainability (Frame and Cavanagh, 2009). The focus of the externalities evaluated in this thesis are local health and environmental impacts of air pollution, and climate change impact from carbon dioxide emissions, all of which are in fact likely to be under-estimated in methodological process (Herbohn, 2005). This means the evaluation of emissions impact on Birmingham may be significantly inaccurate, but this analysis remains appropriate for comparing between competing rail technologies.

There is debate over whether externality evaluation is of any benefit, given the uncertainty and subjectivity involved, in monetisation of non-market goods. The external costs arise, however, due to a failure in the market to include all of the relevant information into decision-making. Therefore, it can be argued that any estimation, however uncertain, helps to highlight that these costs are there and are not being accounted for. Externality evaluation can furthermore help to stimulate the conversation around sustainability. In discussions, monetisation can be a valuable tool to inform and include non-experts in the field of research (Herbohn, 2005; Bebbington et al., 2006; Gasparatos et al., 2007).

The negative impacts which have been included in this evaluation are only concerned with gaseous emissions from fuel production and use, causing localised impacts to human health and the environment, and global climate change impacts. This thesis makes the assumption that propulsion emissions are the highest source of impact caused by rail provision, however these are not the only negative impacts rail provision could cause. A commonly used methodology, Life Cycle Analysis (LCA), provides a more complete means of evaluating impacts, over the full lifecycle of the product, and including all material and energy flows. Although not a necessary part of LCA, it is possible to monetise the results of an LCA analysis, as some of the methods described in Section 3.4.4 of Chapter 3 demonstrate. Significantly, the materials and energy for rolling stock and infrastructure manufacture have been ignored in this analysis, and these could have a high impact on sustainability assessment (Esters and Marinov, 2014). For example, fuel cells require a platinum catalyst - although diesel trains require catalytic converters, which oftentimes also use platinum. There is potentially more complexity to evaluating the sustainability of rail options than is covered in this thesis. A more in-depth analysis based on LCA principles could provide a more detailed appreciation of the potential impacts of rail options.

5.4.2. Internalisation of Rail Externalities

Internalising external costs can achieve two aims: collecting the funds to support the areas of society and environment that suffer the external impacts, and incentivising those creating the externalities to reduce their impacts. The latter is more likely to be achieved if those with the power to make decisions are being penalised. There is the potential issue in rail that introducing a financial penalty to internalise impacts would ultimately be paid for by the passenger through ticket fares. The passengers have no choice on what type of train they take to complete their journey, so this would not create an incentive to decarbonise rail. Furthermore, ticket prices in Britain are already high compared to other European countries, and an increase in fares could move passengers away from rail travel (Butcher, 2020). Introducing a financial penalty to incentivise rail decarbonisation would need to be targeted at the source of decision-making, where changes can be made. At present, the decision-making role is increasingly being taken up by the Government, with the recent suspension of franchise agreements amidst the Covid-19 pandemic (DfT and Shapps, 2020).

Based on the analysis in Section 5.3.2, the average external cost per train-km for the UK rail network is approximately £1.14 for diesel[6], and £0.53 for electric[7] (based on the 2018 electricity grid). The total British rail system normally runs 500 million train-km annually at around 60% electric and 40% diesel (Goddard, 2018), so using this information, a very approximate estimation of the external costs is £390 million per year[8]. If the entirety of diesel rail is converted to fuel cell with renewable hydrogen, £230 million of external costs can be eliminated. This is equivalent to 1% of the whole rail industry expenditure, £21.8 billion, or 10% of the industry rolling stock costs, £2.4 billion, for the year 2018-19 (Office of Rail and Road, 2020b).

There are some measures in place in the UK financial system to account for carbon pricing, though not a direct 'carbon tax', such a fuel duty. However, for these taxes to internalise external impacts, in the strictest sense, the funds raised would need to go directly to the areas where impacts are being caused (Maibach et al., 2008). In reality, the money raised is placed in the 'large tax pot' and distributed per the Government's overall spending budget. The overall spending budget may include elements which help victims of external impacts, such as funding for the National Health Service, but the money is not directly attributable (Lawson-Jones, 2019). Transparency is key to implementing a robust external costing system, where the financial inputs and outputs are clearly defined. This means it is first necessary to identify and quantify every area that is negatively impacted by the activity in question, which is an incredibly complex task. Including external costs into financial decisions in order to reduce the external impacts is a complex process,

[6] Diesel range regional-distance-rural: £ 1.02-1.54-0.87
[7] Electric range regional-distance-rural: £ 0.31-0.83-0.45
[8] This number is merely meant for illustrative purposes, as it does not account for the ranges of values which result from the external cost evaluation.

requiring detailed and nuanced information. It is however, a worthwhile endeavour if it can help to reduce emissions with the aim of limiting the impacts catastrophic climate change (United Nations Framework Convention on Climate Change, 2021). This analysis also only considers external costs of environmental and health impacts from air pollution. There are other external costs which have been excluded from the focus of this study, such as noise costs, safety, congestion, biodiversity impacts, land use, materials, etc.

5.4.3. Considering Local and Global Impacts

The health impacts of air pollution from transport sources have a higher cost in urban environments. This is reflected in the HECT data, which divides its cost factors into urban, sub-urban and rural environments (Korzhenevych et al., 2014). Globally, the greatest air pollution hotspots are cities. For example, an analysis of combustion emissions by Yim and Barrett (2012) demonstrated that air pollution hotspots in the UK are the areas around London, Birmingham, Manchester, Sheffield, and Leeds, five of the UK's largest cities. Low emissions zones (LEZ) or clean air zones (CAZ) are being brought in as a method to limit air pollution in urban environments, generally requiring vehicles to meet a given emissions standard or pay a charge to enter the LEZ/CAZ. In the year 2019-2020, the London LEZ and Ultra-LEZ combined raised a net income of £ 112.5 million, which 'is spent on improving transport in line with the Mayor's Transport Strategy' (Transport for London, 2020). In the strictest sense, this is not a direct internalisation of externalities, but as it is spent on improving public transport, the expenditure aids emissions reduction through improved public transport provision, and hence a further reduction in cars. There is evidence that the ULEZ has reduced nitrogen dioxide pollution by a third in central London, and led to change in vehicle use and improved emissions standards, with a drop of 13,500 polluting vehicles in the ULEZ in its first six months (Greater London Authority, 2019).

The first Clean Air Act was passed in 1956, following the 1952 Great Smog of London, which killed between 8 and 12 thousand people (the Royal College of Physicians, 2016). The second Clean Air Act was passed in 1968, and the first Royal College of Physicians report on air pollution and health dates from 1972. Their most recent report, *Every Breath We Take, the Lifelong Impact of Air Pollution* (2016), highlights that since that first report in 1972 the issue of air pollution has increased, due to the increase in vehicle and energy use, and now in the UK around 40,000 (±25%) deaths per year are attributable to outdoor air pollution, costing the UK more than £20 billion annually. Yet, the conversation around air pollution is limited. The Public Health England (PHE) call to action on reducing air pollution (2018) sets out the role of local government, who have a statutory role in assessing and improving local air quality, the role of health services in helping disseminate understanding of the issues, and the role of the public, who can consider their travel options. There is no mention of the role of national Government besides passing the Clean Air Strategy 2018 (PHE, 2018).

An issue that arises with external cost analysis focused on health impacts of air pollution, is that because, numerically, the damages are greater in urban environments, there is a risk that funding could be diverted towards cities and away from rural communities. This is a regular occurrence in the UK, especially public transport funding: a report into rail infrastructure investment by the House of Commons Transport Committee (2018) found that for the year 2016-17 rail expenditure was £773 *per capita* in London, while the rest of England varied between £70 (East Midlands) and £201 (South East). The choice of external costs analysed is important in this: if the focus lies on local air pollution and health impacts, then urban environments become the focus for change and improvement. However, if the picture is kept wider, and environmental and global climate change impacts are included in external cost analysis focus, this should lead to a more equal distribution of resources. The analysis shows that CO_2e emissions and costing is in most cases higher than localised air pollution, so a focus solely on localised air pollution would ignore the majority of emissions and could be counter-productive, resulting in an increase in climate change pollution.

This juxtaposition of urban and rural environments can influence the decision of traction technology. For example, electric trains do not produce any at use emissions, which means that implementing electric rail can immediately reduce the local impacts of at-use rail emissions. However, the source of emissions is transferred to the source of electricity, and it is not necessarily true that electricity production is low-emission. A study of rail emissions by Esters and Marinov in 2013, found that electric rail caused more pollution overall than their diesel counterparts, particularly high-speed trains, due to the electric grid mix which at the time was highly polluting. Although since 2013 the UK grid has reduced CO_2 emissions by approximately 45% (BEIS, 2020a), so that electric rail now produces less emissions, this study still serves to show that a whole system approach to emissions reduction is necessary. To reduce emissions in one area, it is likely necessary for other areas to decarbonise too - such as electric trains and the electricity production system. This also means that the emissions produced by electric rail can fluctuate rapidly in line with the electric grid mix. Reducing emissions cannot be addressed in isolation, or there is a risk that decarbonising one area could lead to a higher level increase.

5.5. Summary

This chapter presented the first part of the analysis results for this thesis. The objectives addressed were to evaluate both the emissions and external costs from rail, considering diesel, electric and fuel cell traction options. The emissions were calculated and monetised for the mixture of diesel and electric rail which serves the city of Birmingham, illustrating the impacts of rail in an urban environment. The external cost evaluation showed that emissions from rail have an impact on Birmingham costing between one and six million pounds annually.

The next section presented the results of calculating the emissions from rail traction technology options for the defined case studies. Emissions were calculated for diesel rail, electric rail, and fuel cell with seven options for hydrogen production, on a 30-year lifetime basis, and within the boundaries of the three case studies. The comparison of emissions production gave similar results for the three case studies. Overall, this analysis showed that the options which produce the greatest emissions are diesel rail and fuel cell rail with hydrogen produced via grid-electricity electrolysis. The options which produce the lowest emissions are fuel cell rail with hydrogen produced via electrolysis using renewable electricity, fuel cell rail with hydrogen produced onsite via SMR, or electric rail. The evaluation of impacts from rail emissions leads to the same findings as to which rail traction options create the highest and lowest external costs. This means that in the exploration of external costs, fuel cell rail and electric rail are both candidates to reduce rail emissions, and for all three case studies.

Finally, this chapter discussed the value of external cost evaluation, and the implications of the results for British rail. The results for external cost analysis are maintained as ranges of results, to maintain as much information as possible in the evaluation. Although this shows that external cost analysis contains some uncertainty, due to the fact that costing data is based on non-market goods, the values allow for these non-market goods to be included into financial decision-making. External cost evaluation is a valuable tool to account for impacts of market activities, and is worth considering in the global aim to reduce emissions and limit global warming. A potential drawback to highlight in this thesis, is that the methodologies available for analysing external costs could be updated, and accessibility could be improved. This could be an opportune time for a significant update to external costing analysis, to work with the Paris Agreement on limiting emissions and increase uptake of sustainability considerations into financial markets (UN FCCC, 2021). This chapter formed the first part of the analysis for this thesis, and addressed the first part of the aim and objectives. The next chapter focuses on the internal financial cost analysis, and brings the external and internal costs together into the consideration of Overall Costs.

Chapter 6: Results - Internal Cost Analysis and Overall Costs

6.1. Introduction

This chapter presents the second part of the analysis results chapters, and is concerned with the Lifetime and Overall financial costs. The research objectives addressed in this chapter are the evaluation of the internal capital and operational costs, and the examination of Overall Costs, for diesel, electric, and fuel cell rail. The contents of this chapter consider the second part of the research aim, namely to examine the internal costs of rail. Finally, this chapter brings together the consideration of external costs, calculated in the previous chapter, and internal costs into the Overall Cost analysis.

Examination of the emissions and external costs in the previous chapter showed which options for rail traction produced the least emissions and the least external costs. The option with the lowest associated emissions and external costs is fuel cell rail with hydrogen produced onsite via electrolysis with renewable electricity. This solution can be seen as the optimal option for decarbonising rail. However, in the situation where decisions are based on cost factors, there could be a solution to decarbonise rail which produces low emissions and external costs, as well as being financially viable in comparison to the incumbent diesel rail. To this end, first this chapter evaluates the relevant internal costs of traction technology options, over the defined lifetime of 30 years. The cost profiles for each technology option are assembled, to inform a comparison of technologies based purely on Lifetime Costs. The second part of this chapter combines the results from the external cost analysis in the previous chapter, and the internal cost analysis from this chapter, into the evaluation of Overall Costs. The Overall Costs serve as a means of comparing between traction technology options, taking into account internal Lifetime Costs and external costs.

The final part of this chapter discusses the analysis findings, implication of the findings, and the significance of Lifetime and Overall Costing. The discussion covers some of the elements omitted from the analysis and how these could impact the results. The findings from this chapter lead into the next stage of the thesis, which examines the implications of the analysis findings and the conditions to create in order to implement fuel cell rail within a more sustainable transport system. First, the next section presents the results from the analysis of internal costs.

6.2. Internal Cost Analysis

This section addresses the aim of evaluating the internal costs for diesel, electric, and fuel cell rail. The internal cost analysis looks at the capital and operational expenditure necessary to run each option for rail traction. This analysis only includes the relevant costs, that is the costs which are a direct result of the train technology used. This means the results do not portray the full expenditure for rail companies, but serves as a comparison between the options. This analysis was performed using a 30-year lifetime basis, which is the expected lifetime of rail rolling stock. For all of the case studies, the diesel analysis was based on the current rolling stock, and the electric analysis was based on replacement with analogous electric rolling stock, which is currently in-use on the British network. The fuel cell analysis was based on replacement with the Coradia iLint fuel cell trains for the regional and rural routes, and on replacement with mainline fuel cell locomotive data for the long-distance line as was detailed in Chapter 4, Section 4.2. Fuel cell rail was evaluated with the seven options for hydrogen production outlined below:

- Imported hydrogen produced from steam methane reforming (SMR imp H_2)
- Imported hydrogen produced from electrolysis with European Union average grid electricity (Elec imp H_2)
- Onsite production via steam methane reforming, with UK gas grid methane (SMR ons H_2)
- Onsite production via electrolysis, with UK grid electricity (Elec ons H_2)
- Onsite production via electrolysis, with solar power (Solar H_2)
- Onsite production via electrolysis, with onshore wind power (On wind H_2)
- Onsite production via electrolysis, with offshore wind power (Off wind H_2)

To estimate the costs of onsite hydrogen production, the costs of reformer and electrolysis facilities were calculated based on the annual hydrogen consumption for each case study, and the hydrogen production capacity of reformer and electrolysis facilities from Kent et al. (2016). The cost of onsite production with renewable energy includes the cost of the electrolysis facility, and the cost of renewable power generation. Load factors for the types of renewable have been accounted for, based on the UK installed renewable capacity load factors for 2018 (Department for Business, Energy and Industrial Strategy, 2021). Each option for renewable generation was calculated separately, assuming 100% electricity provision for the case study. However, a more efficient system would be formed of a combination of solar and wind generation, to enable production under different meteorological conditions.

6.2.1. Capital Cost Analysis

For the capital cost analysis, each traction technology option requires different infrastructure, in addition to the rolling stock, meaning there are different investment necessities. For diesel rail, it is assumed that all necessary infrastructure is already in place, so the capital required is only for purchasing the rolling stock. For electric rail, for all three case studies the majority of the tracks are not electrified, so there is the additional cost of electrifying the tracks as well as the rolling stock costs. For fuel cell rail, there is no trackside infrastructure, but there is the hydrogen refuelling infrastructure, which is required for all hydrogen production options. In addition, the options for producing hydrogen onsite require infrastructure, namely reformers, electrolysers, solar panels, and wind turbines, which is defined for each option.

The number of trains required for each case study changes depending on the fuel traction option. For all case studies, the number of diesel trains was based on like for like replacement of current fleet numbers. For electric rail, the number of trains required was based on the number of return trips undertaken daily, and length of time to complete a return trip. As electric trains are not limited by range capacity, and are more reliable than diesel trains, it has been assumed they can run the route continuously from end to end (during service hours). In the case of fuel cell rail, the number of trains needed was estimated based on the reported range of the iLint and fuel cell locomotive trains, the maximum daily mileage currently travelled by trains to provide the service, and maintaining current passenger capacity levels. The estimation of fuel cell train numbers also took into account the distance of the full line length, especially in the long-distance case study, to ensure that there are sufficient trains to provide a full length of the service, without needing to change trains halfway down (or up) the country. Ensuring there are sufficient trains ensures replacing diesel rail with fuel cell can maintain the same level of service, but if train refuelling during the day could be introduced then the number of fuel cell trains needed could be reduced.

The cost of electrification was estimated in two manners. The first is in the situation where lines continue to be electrified one at a time, so this is the estimation for if the case study service were solely responsible for electrification costs. The second method assumes a situation where electrification is happening across the country, and the costs for electrifying the lines are shared between all of the subsequently electrified services which use the lines. In reality the lines are electrified by Network Rail, which is independent from the daily operation of services, but as the analysis covers the cost of supplying the rail service, this method assigns an electrification cost to the service of interest. The first option is defined as the maximum value and the second option as the minimum value. For the first situation, the estimated length of track to electrify was calculated as the length of route which is not electrified, times the number of tracks which make up the route. For the second situation, an equivalent length of track to electrify was estimated, which took into account the portions of shared route, and the proportion of use on the shared routes. Table 6.1 details the numbers of trains estimated for each case study, and the length of non-electrified route and track type, and hence track to electrify.

Table 6.1: Capital costing details.

	Regional case study	Long-distance case study	Rural case study
Number of diesel trains	35	50	20
Number of electric trains	25	32	15
Number of fuel cell trains	37	64	15
Total length of route	166 km	1,380 km	273 km
Route to electrify	154 km	969 km	260 km
Track type[9]	92% 2x, 8% 4x	100% 2x	80% 1x, 20% 2x
Track to electrify - max	333 km	1,940 km	312 km
Track to electrify - min	312 km	457 km	226 km

1x refers to single track lines, 2x to double track, and 4x to four-track.

The following example calculation details the process which was used to calculate the electrification capital cost for the regional case study.

Example Calculation

- The capital cost per km of single track was worked out based on the average costs that could be found in the literature for planned and completed real electrification projects (details in Appendix 4, A4.2): 1,626,064 £/km[10]
- The amount of the route that is not yet electrified was estimated using Google Maps (Google, 2021): 154 km (93% of the whole route)
- The proportion of the track that is single, double, or quadruple was also estimated using Google Maps (Google, 2021): 92% double, 8% quadruple

$$Total\ track\ to\ electrify = route \times number\ of\ tracks$$

$$= (154\ km \times 2 \times 0.92) + (154\ km \times 4 \times 0.08) = 333\ km$$

[9] Track type refers to the number of rail tracks on the section of line, commonly double (2x) or single (1x).
[10] This number is based on the electrification costs of real projects within GB. The NR Traction Decarbonisation Strategy (2020) also sets electrification costs at between £1 and 2.5 million per single km.

$$Electrification\ cost = track\ to\ electrify \times cost\ per\ km$$

$$= 333\ km \times 1{,}626{,}064\ £/km \approx £541{,}000{,}000$$

The electrification costs were also estimated following an idealised scenario where the whole rail network is electrified and the cost of electrifying each route is shared between all services using the route, proportionally to each services' usage of the route. The proportion of route shared with other services, and the share of usage on the shared route, were estimated using the train data in Appendix 1, A1.1. For the regional route, it was estimated that 20% of the route is shared, and that the case study has a 76% share of the usage on that shared route. This means a new equivalent track length was calculated to account for the shared route:

$$Track\ to\ electrify\ with\ shared\ costs$$

$$= unshared\ track + (shared\ track \times share\ of\ use)$$

$$= (333\ km \times 0.8) + (333\ km \times 0.2 \times 0.76) \approx 312\ km$$

$$Shared\ electrification\ cost = 312\ km \times 1{,}626{,}064\ £/km \approx £507{,}000{,}000$$

The other electrification costs were calculated following this procedure. The rest of the capital costs were calculated in similar manners, in that the cost per unit and the number of units are defined directly, or from estimations using the literature data. Details of the input data for capital cost estimation are presented in Appendix 4, including a detailed table of results in A4.4. Tables 6.2 to 6.7 summarise the capital cost results as relevant to each rail traction option. Tables 6.2, 6.3 and 6.4 outline the costs for diesel, electric, and fuel cell (divided between imported hydrogen or hydrogen produced onsite), and Tables 6.5, 6.6 and 6.7 detail the capital costs which are included in each hydrogen production option.

Table 6.2: Capital costs, regional case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Rolling Stock	59.4	37.5	177	177
Track Infrastructure	-	507 - 541	-	-
Refuelling Infrastructure	-	-	5.23	5.23
Onsite H_2 production	-	-	-	13 - 13.1
Renewable electricity for H_2	-	-	-	26.3 - 55.5
Total	59.4	545 - 579	182	195 - 251

- refers to a non-applicable cost.

Table 6.3: Capital costs, long-distance case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Rolling Stock	216	136	246	246
Track Infrastructure	-	1,680 - 7,110	-	-
Refuelling Infrastructure	-	-	19.2	19.2
Onsite H_2 production	-	-	-	110 - 111
Renewable electricity for H_2	-	-	-	223 - 471
Total	216	1,820 - 7,250	265	375 - 847

- refers to a non-applicable cost.

Table 6.4: Capital costs, rural case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Rolling Stock	34	22.5	71.6	71.6
Track Infrastructure	-	429 - 607	-	-
Refuelling Infrastructure	-	-	5.23	5.23
Onsite H_2 production	-	-	-	5.58 - 5.64
Renewable electricity for H_2	-	-	-	11.3 - 23.8
Total	34	452 - 630	76.8	82.4 - 106

- refers to a non-applicable cost.

The capital cost for fuel cell trains is a range, due to the variety of potential hydrogen sources included in this analysis. Importing hydrogen gives the lowest capital cost, as there is less infrastructure required. The following example calculation shows how the capital cost for fuel cell rail with hydrogen produced via electrolysis with onshore wind power was calculated. Further detail of the input factors for hydrogen production options can be found in Appendix 4, A4.3. Costs were found for different types of electrolyser (polymer electrolyte, alkaline, and solid oxide), the average of these is used for this analysis, meaning that actual electrolyser prices can be higher or lower than those illustrated in this example (Walker et al., 2018). Tables 6.5, 6.6 and 6.7 give summaries of the capital costs for onsite hydrogen production options, as imported hydrogen costs have been considered in Tables 6.2 to 6.4.

Example Calculation

- Capital cost for the fuel cell rail option with hydrogen produced from onsite electrolysis with renewable electricity produced from onshore wind, for the regional case study
- The capital cost per kW for the electrolyser was calculated based on the average of costing data found in the literature, as detailed in Appendix 4, A4.3: 892 £/kW
- The production rate for the electrolyser was calculated based on the average of the electrolysers used for the costing data (Appendix 4, A4.3): 48 kW/kgH_2
- The annual hydrogen consumption has been calculated based on distance, train formations, and train consumption (Appendix 1): 1,608,596 kg/y
- The electrolyser is assumed to run 15 h/day, 350 days/year: 5,250 h/y
- The onshore wind load factor is 28.4% (BEIS, 2021)
- The capital cost per kW for the onshore wind farm was calculated based on the average of capital costs for wind farm projects found in the literature (Appendix 4, A4.3): 835 £/kW

$$Hourly\ H_2\ production\ rate = annual\ H_2\ consumption \div running\ hours$$

$$= 1{,}608{,}596\ kgH_2 \div 5{,}250\ h \approx 306\ kgH_2/h$$

$$Electrolyser\ size\ (kW) = hourly\ H_2 \times average\ production\ rate$$

$$= 306\ kgH_2 \times 48\ kW/kgH_2 = 14{,}688\ kW$$

$$Electrolyser\ cost = electrolyser\ size \times average\ cost\ per\ kW$$

$$= 14{,}688\ kW \times 892\ £/kW \approx £13{,}100{,}000$$

$$Annual\ energy\ for\ electrolysis\ (kWh) = electrolyser\ power \times running\ hours$$

$$= 14{,}688\ kW \times 5{,}250h = 77{,}100{,}000\ kWh$$

$$Annual\ wind\ production\ hours = annual\ hours \times load\ factor$$

$$= (365 \times 24)h \times 0.284 = 2{,}450\ h$$

$$Wind\ farm\ size\ (kW) = annual\ energy \div annual\ production\ hours$$

$$= 77{,}100{,}000\ kWh \div 2{,}450\ h = 31{,}500\ kW$$

$$Wind\ farm\ cost = wind\ farm\ size \times wind\ farm\ average\ cost\ per\ kW$$

$$= 31{,}500\ kW \times 835\ £/kW \approx £26{,}300{,}000$$

Table 6.5: Capital costs of onsite hydrogen production, regional case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Rolling stock	177	177	177	177	177
Refuelling infrastructure	5.23	5.23	5.23	5.23	5.23
SMR facility	13.0	-	-	-	-
Electrolysis facility	-	13.1	13.1	13.1	13.1
Solar farm	-	-	55.5	-	-
Onshore wind farm	-	-	-	26.3	-
Offshore wind farm	-	-	-	-	49.7
Total	195	195	251	222	245

- refers to a non-applicable cost.

Table 6.6: Capital costs of onsite hydrogen production, long-distance case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Rolling stock	246	246	246	246	246
Refuelling infrastructure	19.2	19.2	19.2	19.2	19.2
SMR facility	110	-	-	-	-
Electrolysis facility	-	111	111	111	111
Solar farm	-	-	471	-	-
Onshore wind farm	-	-	-	223	-
Offshore wind farm	-	-	-	-	421
Total	375	376	847	599	797

- refers to a non-applicable cost.

Table 6.7: Capital costs of onsite hydrogen production, rural case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Rolling stock	71.6	71.6	71.6	71.6	71.6
Refuelling infrastructure	5.23	5.23	5.23	5.23	5.23
SMR facility	5.58	-	-	-	-
Electrolysis facility	-	5.64	5.64	5.64	5.64
Solar farm	-	-	23.8	-	-
Onshore wind farm	-	-	-	11.3	-
Offshore wind farm	-	-	-	-	21.4
Total	82.4	82.5	106	93.8	104

- refers to a non-applicable cost.

As would be expected, in all three cases diesel rail has the lowest capital cost as there are no additional infrastructure requirements. For all three case studies, track electrification is the greatest cost between all traction options. The electrification cost range reflects the two methods of calculation, as a line-only solo project or a national project. The range is small for the regional and rural case studies, which illustrates that these rail lines are mainly used by the service in question. However, the range is significant for the long distance route, which demonstrates that much of this track is shared with other services - and that while electrifying just the long route would be prohibitively expensive, a coordinated programme of electrification covering networks around the whole of Britain could prove more cost-effective. Section 6.4 discusses the potential effects of a rolling programme of electrification, including the Electrification Cost Challenge report but the Rail Industry Association, which sets out that a rolling programme could reduce electrification costs by 33 to 50% (RIA, 2019).

Based purely on capital costing, diesel trains are clearly the cheapest option due to the lack of additional infrastructure requirements. Electrification of track makes electric rail between 10 and 20 times more expensive than diesel on capital alone, showing that this is a significant investment. This is an important depiction of diesel trains benefitting from incumbent technology advantage, as the necessary infrastructure is already in place. The capital cost for fuel cell rail is also higher than diesel, although only around double for imported hydrogen and around three or four times more for onsite hydrogen produced from renewable sources. The next section concerns the analysis of operational costs.

6.2.2. Operational Cost Analysis

The procedure for calculating operational costs is different from capital costing. The capital costs are a one-off cost, however the operational costs were first calculated on an annual basis, and then multiplied to the 30-year lifetime. Future discounting of financial values has not been taken into account in this analysis, as this analysis concerns a full cost accounting procedure to evaluate environmental impact into decisions, as detailed in Chapter 3. The main operational costs which vary between rail traction technology options are fuel costs, track charges, and rolling stock maintenance costs. Diesel and fuel cell rail have additional costs associated with the upkeep of refuelling infrastructure, while electric rail has costs of maintaining the electrification infrastructure, which are also included. Track charges are costs which are paid by the Train Operating Companies to Network Rail, and are based in part on train weights, as this affects the track maintenance required (NR, 2020b). As these have not yet been published for fuel cell trains, the track charges for fuel cell rail was based on data for a train of similar weight. The calculation below shows an example of the procedure for calculating electricity costs for the regional case study. Appendix 5 details the input data and results of the operational cost analysis, including a detailed table of results in A5.5. Tables 6.8, 6.9 and 6.10 present summaries of the operational costs evaluated for each case study over the 30-year lifetime.

Example Calculation

- Operational cost of electricity for the regional case study
- BEIS (2020b) reports the industrial price of electricity: 0.129 £/kWh
- Class 350 Electric Multiple Unit (assumed replacement for current diesel) energy usage from Hobson et al. (2001): 6.56 kWh/train-km
- Travel distance calculated (Appendix 1, A1.1): 3,829,990 km/y

$$Annual\ energy\ use = annual\ distance \times train\ energy\ use$$

$$= 3{,}829{,}990\ km/y \times 6.56\ kWh/km = 25{,}124{,}700\ kWh/y$$

$$Annual\ electricity\ cost = annual\ energy\ use \times electricity\ price$$

$$= 25{,}124{,}700\ kWh \times 0.129\ \text{£}/kWh \approx \text{£}3{,}240{,}000$$

$$Lifetime\ electricity\ cost = annual\ electricity\ cost \times 30$$

$$= \text{£}3{,}240{,}000 \times 30 = \text{£}97{,}200{,}000$$

The remaining operational costs were calculated in a similar manner based on the data available, as detailed in Appendix 5.

Table 6.8: Operational costs over 30 years, regional case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Fuel (imported)	138	97.2	342	75.1 - 196
Onsite fuel production	-	-	-	29.9 - 47.7
Track Charges	15.6	34.9	40.3	40.3
Maintenance - rolling stock	423	188	88.5	88.5
Maintenance - infrastructure	0.56	5.43	9.73	9.73
Total	577	326	481	168 - 335

- refers to a non-applicable cost.

Table 6.9: Operational costs over 30 years, long-distance case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Fuel (imported)	1,100	726	2,900	638 - 1,660
Onsite fuel production	-	-	-	254 - 405
Track Charges	274	331	393	393
Maintenance - rolling stock	996	550	282	282
Maintenance - infrastructure	1.12	33.2	19.5	19.5
Total	2,370	1,640	3,590	948 - 2,350

- refers to a non-applicable cost.

Table 6.10: Operational costs over 30 years, rural case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Fuel (imported)	75.8	86.4	147	32.3 - 84
Onsite fuel production	-	-	-	12.8 - 20.5
Track Charges	8.01	14.7	26.9	26.9
Maintenance - rolling stock	254	167	52.8	52.8
Maintenance - infrastructure	0.56	2.45	9.73	9.73
Total	338	271	236	102 - 173

- refers to a non-applicable cost.

The cost of imported hydrogen does not differentiate between the ways that imported hydrogen is produced, due to the availability of data, so for the operational cost evaluation a single option of imported hydrogen fuel was considered. The different options for producing hydrogen onsite have different operational costs, reflected in the ranges shown in the tables above. The example calculation below shows the procedure for calculating the operational cost of methane fuel to produce hydrogen onsite via SMR. Details of operational costs for hydrogen production options can be found in Appendix 5, A5.4. For the options which produce hydrogen from imported fuel, namely SMR and electrolysis with grid electricity, the operational cost is the cost of methane or electricity respectively. For the renewable electricity options, the costs arise from operating and maintaining the renewable energy equipment. Tables 6.11, 6.12 and 6.13 detail the operational costs for the onsite hydrogen production options for the three case studies.

Example Calculation

- Operational costs for FC rail with the option of hydrogen produced onsite via SMR, for the regional case study
- The annual hydrogen consumption was calculated based on annual mileage and train fuel consumption (Appendix 1): 1,608,596 kg/y
- The natural gas consumption, and hydrogen production rate, per SMR unit was reported by Kent et al. (2016): 1,726 kW/unit and 231,350 kgH_2/unit/year
- Assuming hydrogen is produced 24h/day, 350 days/year: 8,400 h/y
- BEIS (2020b) reports the average natural gas price for industry: 0.02484 £/kWh

$$Number\ of\ units\ needed$$

$$= annual\ hydrogen\ consumption \div annual\ hydrogen\ production\ per\ unit$$

$$= 1{,}608{,}596\ kgH_2 \div 231{,}350\ kgH_2/unit = 7\ units$$

$$Annual\ gas\ consumption$$

$$= gas\ input \times number\ of\ units \times annual\ production\ hours$$

$$= 1{,}726\ kW \times 7 \times 8{,}400\ h \approx 101{,}489{,}000\ kWh$$

$$Annual\ gas\ cost = annual\ consumption \times gas\ price$$

$$= 101{,}489{,}000\ kWh \times 0.02484\ £/kWh \approx £2{,}520{,}000$$

$$Lifetime\ gas\ cost = annual\ gas\ cost \times 30 = £2{,}520{,}000 \times 30 \approx £75{,}600{,}000$$

Table 6.11: Operational costs of hydrogen production over 30 years, regional case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Fuel (imported)	75.6	196	-	-	-
Onsite fuel production	-	-	29.9	35.7	47.7
Track Charges	40.3	40.3	40.3	40.3	40.3
Maintenance - rolling stock	88.5	88.5	88.5	88.5	88.5
Maintenance - infrastructure	9.73	9.73	9.73	9.73	9.73
Total	214	335	168	174	186

- refers to a non-applicable cost.

Table 6.12: Operational costs of hydrogen production over 30 years, long-distance case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Fuel (imported)	638	1,660	-	-	-
Onsite fuel production	-	-	254	305	405
Track Charges	393	393	393	393	393
Maintenance - rolling stock	282	282	282	282	282
Maintenance - infrastructure	19.5	19.5	19.5	19.5	19.5
Total	1,330	2,350	948	999	1,099

- refers to a non-applicable cost.

Table 6.13: Operational costs of hydrogen production over 30 years, rural case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Fuel (imported)	32.3	84.0	-	-	-
Onsite fuel production	-	-	12.8	15.4	20.5
Track Charges	26.9	26.9	26.9	26.9	26.9
Maintenance - rolling stock	52.8	52.8	52.8	52.8	52.8
Maintenance - infrastructure	9.73	9.73	9.73	9.73	9.73
Total	122	173	102	105	110

- refers to a non-applicable cost.

The operational costs for electric rail are consistently lower than for diesel. Although electricity is more expensive than diesel fuel, the operational costs are lower due to the higher efficiency of electric rail. Electric trains also have lower maintenance costs, but higher track charges. For the rural case study, the electricity cost is higher than that calculated for diesel. This is due to the fact that the current diesel trains in operation are formed of two carriages, whereas the standard minimum for an electric train is three carriages - meaning this higher cost does also come with the added benefit of increased passenger capacity. Despite the higher electricity costs for this case, the lower maintenance costs over the lifetime of the rolling stock means that the operational costs are overall lower for electric than diesel.

Comparison of the operational costs for fuel cell rail depends on the source of hydrogen, and is not consistent between case studies. In all cases, the operational costs for hydrogen produced via electrolysis with renewable electricity are the lowest, due to the fact that these options are not subject to fuel costs. This also means these options would not be affected by sudden changes to fuel prices, and the energy crisis seen in the UK in 2021 has shown that both liquid fuels and grid electricity prices can be subject to volatile pricing and fragile distribution markets (Energy Saving Trust, 2021). For the regional case study, fuel cell rail with imported hydrogen has a higher operational cost than electric rail but lower than diesel. For the long-distance case study the imported hydrogen option has the highest operational cost of all, and for the rural case study fuel cell rail has a lower operational cost than both diesel and electric rail regardless of hydrogen source. Detailed discussion on the relative costs of traction technology options forms part of the next section, which integrates the capital and operational costs into the Lifetime Cost analysis.

6.2.3. Lifetime Cost Analysis

The previous two sections presented the results of the capital cost analysis and the operational cost analysis, respectively. These costs were assembled in this section to calculate the Lifetime Cost analysis, addressing the research objective of evaluating the internal costs for diesel, electric and fuel cell rail. The previous section showed that the comparison of costs between rail traction technology options varied between the capital and operational costs, and varied depending on hydrogen source and case study specifics. This shows that the analysis of Lifetime Costs is a useful metric to include the variations in costs which occur at different points throughout the lifetime of the asset.

The Lifetime Costs were the sum of the capital costs calculated in Section 6.2.1 and the operational costs calculated over the 30-year lifetime in Section 6.2.2. Tables 6.14, 6.16 and 6.18 present the results of the Lifetime Cost analysis, with detailed costs for the different hydrogen production options presented in Tables 6.15, 6.17 and 6.19.

Table 6.14: Lifetime Costs, regional case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Capital Cost	59.4	545 - 579	182	195 - 251
Operational Cost	577	326	481	168 - 335
Lifetime Internal Cost	637	870 - 904	662	396 - 530

Table 6.15: Lifetime Costs for hydrogen production options, regional case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Capital Cost	195	195	251	222	245
Operational Cost	214	335	168	174	186
Lifetime Internal Cost	409	530	419	396	431

Table 6.16: Lifetime Costs, long-distance case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Capital Cost	216	1,820 - 7,250	265	375 - 847
Operational Cost	2,370	1,640	3,590	948 - 2,350
Lifetime Internal Cost	2,590	3,460 - 8,890	3,860	1,600 - 2,730

Table 6.17: Lifetime Costs for hydrogen production options, long-distance case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Capital Cost	375	376	847	599	797
Operational Cost	1,330	2,350	948	999	1,100
Lifetime Internal Cost	1,710	2,730	1,800	1,600	1,900

Table 6.18: Lifetime Costs, rural case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Capital Cost	34	452 - 630	76.8	82.4 - 106
Operational Cost	338	271	236	102 - 173
Lifetime Internal Cost	372	722 - 900	313	199 - 256

Table 6.19: Lifetime Costs for hydrogen production options, rural case study.

£millions	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Capital Cost	82.4	82.5	106	93.8	104
Operational Cost	122	173	102	105	110
Lifetime Internal Cost	204	256	208	199	214

Despite having lower operational costs, on a Lifetime Cost basis, electric traction is consistently the most expensive option, due to the high costs of electrification. On the other hand, for all three case studies, the option with the lowest Lifetime Costs is fuel cell rail with hydrogen produced onsite from electrolysis using renewable electricity, or produced onsite via SMR. The lowest cost renewable energy option is onshore wind, but all three renewable options prove to have lower Lifetime Costs than the more polluting rail traction options. This means the findings of exploring the internal costs of rail, show that fuel cell rail can be economically viable on a Lifetime Cost basis.

An element which has not been addressed in this analysis, is that the expected lifespan of electrification infrastructure is greater than the 30-year basis of this analysis. The expected lifespan of electrified track is 60 years, with extensive refurbishment every 20-30 years (Keenore, 2016). Basing the electrification infrastructure cost on a 60-year rather than 30-year lifespan would reduce the capital cost by half, not including the 'extensive refurbishment' cost. For illustration, the Lifetime Costs of electric rail, including an option with half the value for capital cost of electrification calculated in Section 6.2.1, is included in the following three diagrams comparing the Lifetime Costs.

Figures 6.1, 6.2, and 6.3 illustrate the Lifetime Costs tabulated in Tables 6.14 to 6.19 above. These three diagrams include an error bar, which represents the electrification cost range depending on whether electrification is a solo or a national project (Section 6.2.1). These graphs show the relative capital and operational costs, and show that diesel rail has comparatively lower capital costs despite having higher Lifetime Costs. These graphs also show that even if the electrification costs are estimated on a 60-year rather than 30-year basis, electric rail remains an expensive option for decarbonisation. For the regional case study, electric rail becomes more cost effective against diesel rail, but for the other two case studies electric rail remains more expensive than diesel rail, and in all cases fuel cell rail with renewably-produced hydrogen, or hydrogen via SMR, remain the lowest Lifetime Cost options.

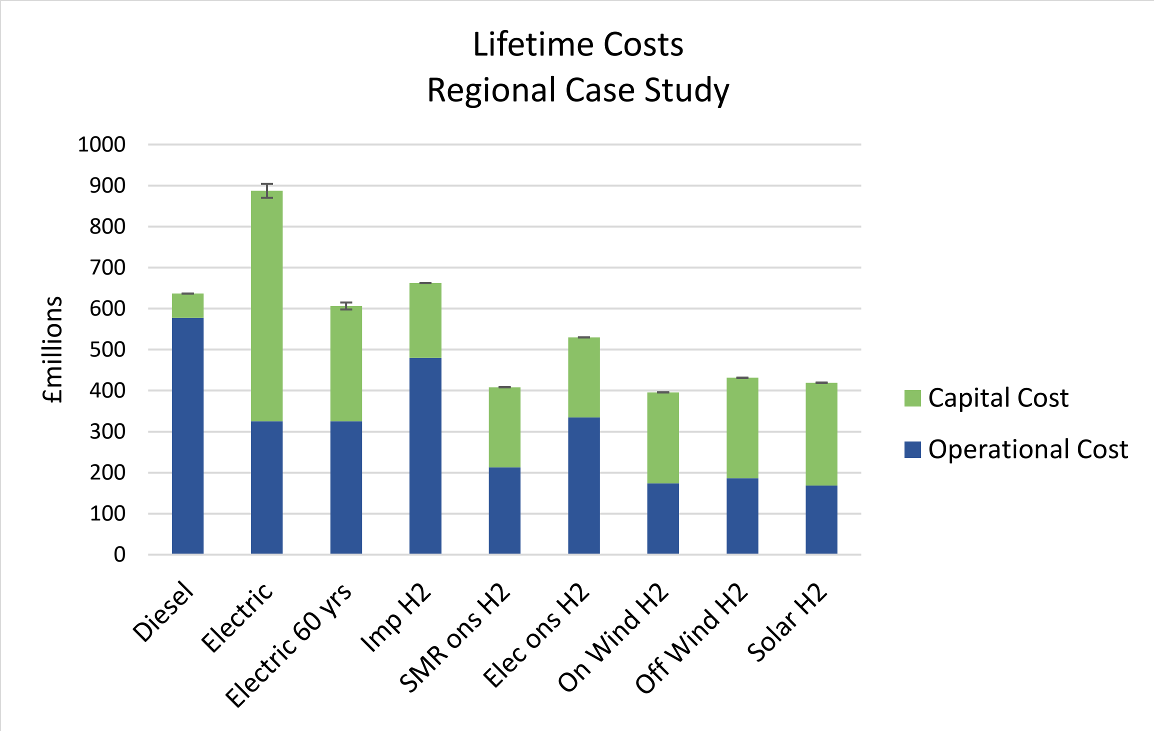

Figure 6.1: Lifetime Cost analysis, regional case study.

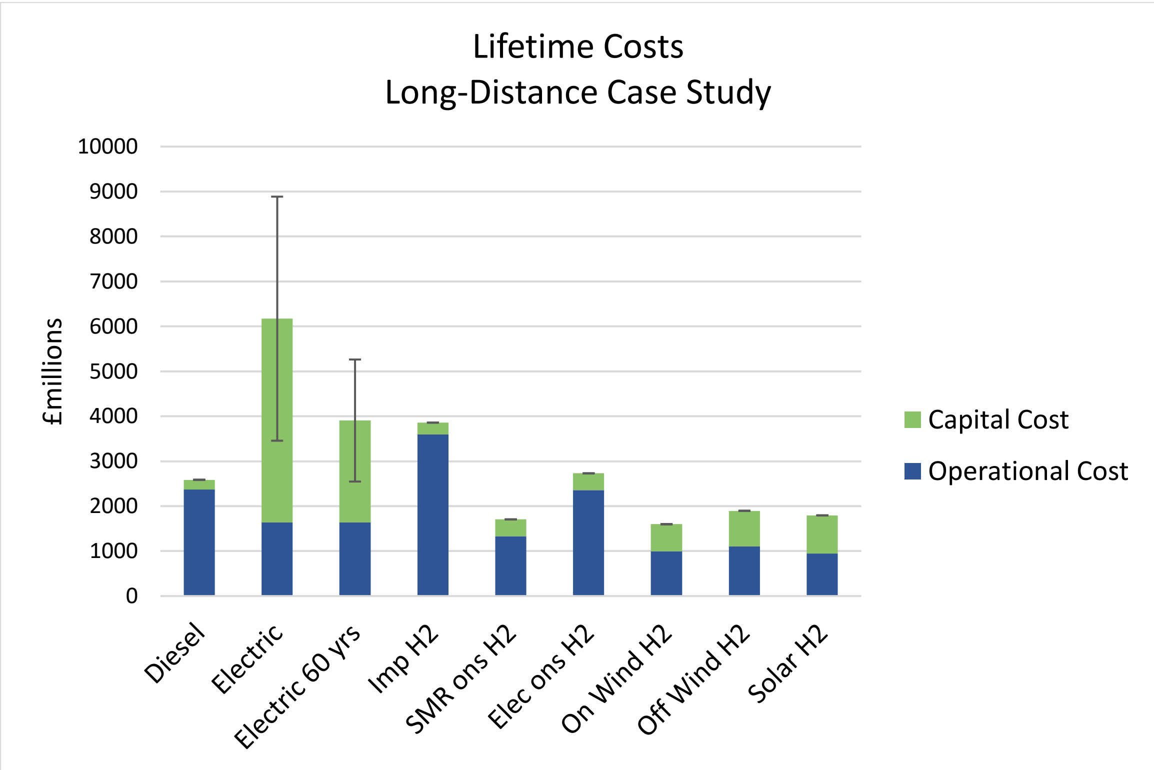

Figure 6.2: Lifetime Cost analysis, long-distance case study.

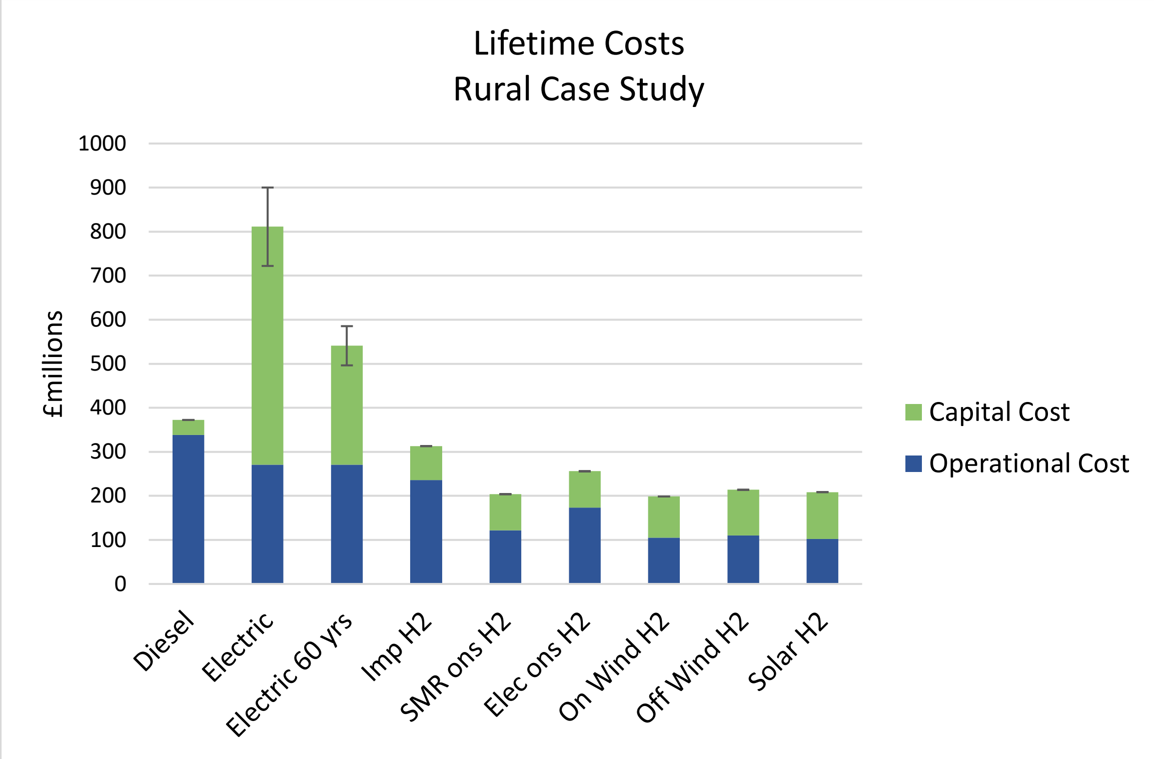

Figure 6.3: Lifetime Cost analysis, rural case study.

These diagrams show the relative differences between capital and operational costs within the Lifetime Cost analysis. The capital costs for fuel cell rail are overall near to 50% of the Lifetime Costs, whereas for diesel the capital costs are only around 10% of the Lifetime Costs. Despite having a lower Lifetime Cost, this relatively higher capital remains a disadvantage for fuel cells. The fact that fuel cell rail requires a higher upfront cost can be seen as a risk for investment in fuel cell rail, especially as the technology is still in development. This is an area where the Government can provide guarantees to help with investment, which is a subject of discussion in Chapter 7. This investment difference is less pronounced for the long-distance route, due to the higher mileage and hence higher operational costs, although the Lifetime Costs involved in this case study are significantly higher than the other two cases. The internal analysis of costs shows that on a lifetime basis, fuel cell rail has the potential to be financially viable compared to both diesel and electric rail, even without the consideration of externalities. The next section presents the results of the Overall Analysis, which takes into account the Lifetime Costs from this section, and the external costs calculated in Chapter 5.

6.3. Overall Cost Analysis

As a culmination of the exploration of internal and external dimensions of cost for British rail, this section conglomerates the internal costs calculated in Section 6.2.3 and the external costs calculated in Section 5.3.2 into the analysis of Overall Costs. This analysis allows for the financial comparison of options for rail traction, taking into consideration internal Lifetime Costs, and external cost impacts of emissions. This section also addresses the research objective of examining the Overall Costs of rail, for diesel, electric and fuel cell rail. The hypothesis for this analysis was that external costs would need to be included into the analysis of costs, in order to make the less polluting options financially advantageous. However, the analysis so far has shown that the options for rail traction which produce the least emissions and least externalities, and the options with the lowest Lifetime Costs, are the same options. Namely, fuel cell rail with hydrogen produced onsite, via electrolysis using renewable power, and via SMR. Nonetheless, evaluating the Overall Costs shows a financial comparison of options, with a greater depth of consideration for the impacts caused by the rail options studied. Tables 6.20, 6.22 and 6.24 present the Overall Costs for the three case studies, and Tables 6.21, 6.23 and 6.25 detail the different options for hydrogen production.

Table 6.20: Overall Costs, regional case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Internal Cost	637	870 - 904	662	396 - 530
External Cost	86.2 - 149	20 - 50.7	52.5 - 319	0 - 156
Overall Cost	723 - 786	890 - 955	715 - 981	396 - 686

Table 6.21: Overall Costs for hydrogen production options, regional case study.

£millions	SMR imp H_2	Elec imp H_2	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Internal Cost	662	662	409	530	419	396	431
External Cost	52.5 - 90.8	157 - 319	20.6 - 43	61.8 - 156	0	0	0
Overall Cost	715 - 753	819 - 981	430 - 452	592 - 686	419	396	431

Table 6.22: Overall Costs, long-distance case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Internal Cost	2,590	3,460 - 8,890	3,860	1,598 - 2,730
External Cost	344 - 614	145 - 374	314 - 2,670	0 - 1,320
Overall Cost	2,930 - 3,200	3,610 - 9,260	4,170 - 6,530	1,598 - 4,050

Table 6.23: Overall Costs for hydrogen production options, long-distance case study.

£millions	SMR imp H_2	Elec imp H_2	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Internal Cost	3,860	3,860	1,710	2,730	1,795	1,598	1,896
External Cost	314 - 418	1,300 - 2,670	99.4 - 160	511 - 1,320	0	0	0
Overall Cost	4,170 - 4,280	5,160 - 6,530	1,810 - 1,870	3,240 - 4,050	1,795	1,598	1,896

Table 6.24: Overall Costs, rural case study.

£millions	Diesel	Electric	Fuel Cell - Imported H_2	Fuel Cell - Onsite H_2
Internal Cost	372	722 - 900	313	199 - 256
External Cost	43.1 - 77.6	17.2 - 44.4	24.6 - 135	0 - 66.5
Overall Cost	415 - 450	739 - 944	338 - 448	199 - 323

Table 6.25: Overall Costs for hydrogen production options, rural case study.

£millions	SMR imp H_2	Elec imp H_2	SMR ons H_2	Elec ons H_2	Solar H_2	On wind H_2	Off wind H_2
Internal Cost	313	313	204	256	208	199	214
External Cost	24.6 - 47.6	65.7 - 135	10.1 - 23.6	25.7 - 66.5	0	0	0
Overall Cost	338 - 361	379 - 448	214 - 228	282 - 323	208	199	214

The comparisons made between rail traction technology options on an Overall Cost analysis basis are very similar to those made for the Lifetime Cost analysis. On a general comparison of Overall Costs, the highest cost options for rail traction are electric rail, diesel rail, and fuel cell rail with imported hydrogen. The lowest cost options are fuel cell rail with hydrogen produced onsite, whether through SMR or electrolysis with renewable electricity. Additionally, for the regional case study, fuel cell rail with hydrogen produced via electrolysis using UK grid electricity has lower Overall Costs than diesel, and for the rural case study, fuel cell rail has lower Overall Costs regardless of the source of hydrogen. In contrast, for the long-distance route, fuel cell rail is only financially viable against diesel if the hydrogen is produced from onsite SMR or onsite electrolysis with renewable electricity. The Overall Cost analysis helps to solidify the financial advantage of fuel cell rail over diesel rail.

The Overall Costs presented in Tables 6.20 to 6.25 are illustrated graphically in Figures 6.4, 6.5 and 6.6. The Overall Costs are separated into capital costs, operational costs, external costs from ExternE, and carbon costs (central values) - the latter two divided by upstream impacts and downstream impacts. For all case studies, the rail traction options with the lowest internal costs also produce the lowest external costs, namely fuel cell with hydrogen produced from renewable energy or SMR. The graphs show that the estimated external costs are a small proportion of Overall Costs. For each traction technology that produces externalities, the proportion of external costs within the Overall Costs, between the three case studies, is on average:

- Diesel: 14%
- Electric: 4%
- Fuel cell with SMR imp H_2: 10%
- Fuel cell with elec imp H_2: 24%
- Fuel cell with SMR ons H_2: 8%
- Fuel cell with elec ons H_2: 15%

The higher proportion of externalities are produced by diesel rail and fuel cell rail with hydrogen produced by electrolysis using grid electricity, whether imported or onsite. As the external costs are proportionally higher for these technologies, inclusion of external costs into market pricing would have the greatest impact on the financial comparison of these options.

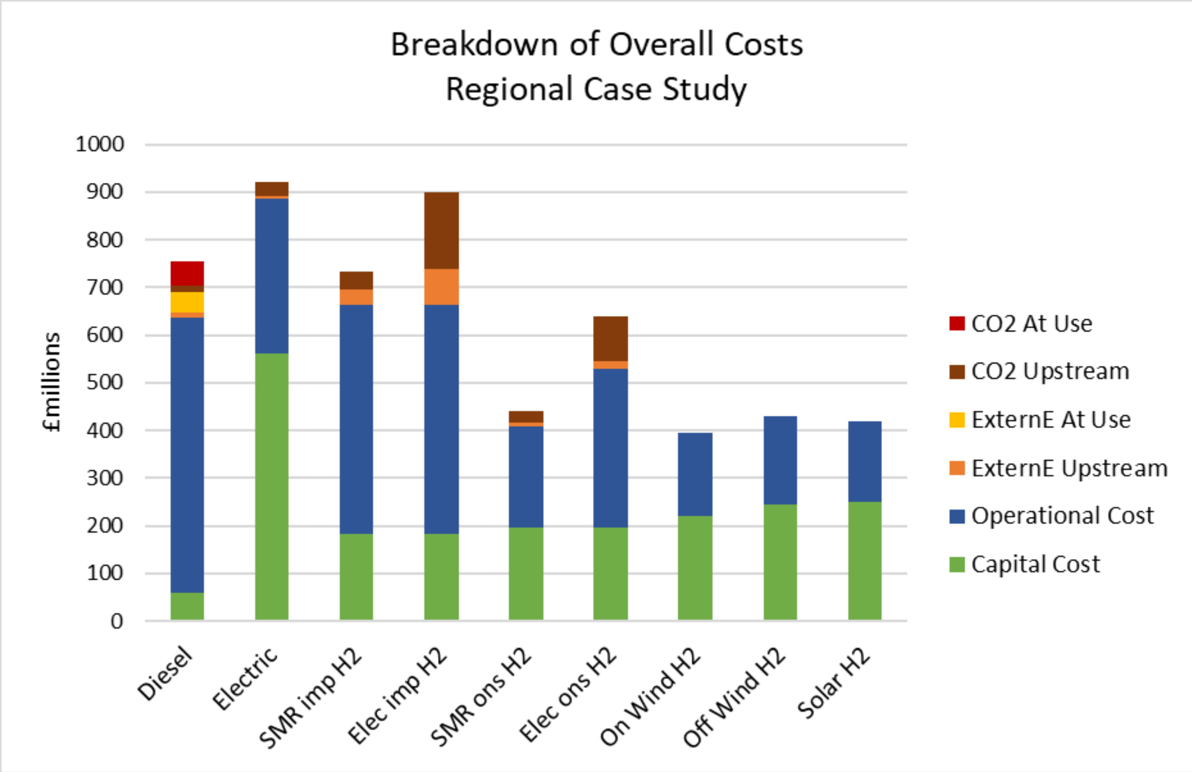

Figure 6.4: Overall Cost analysis, regional case study.

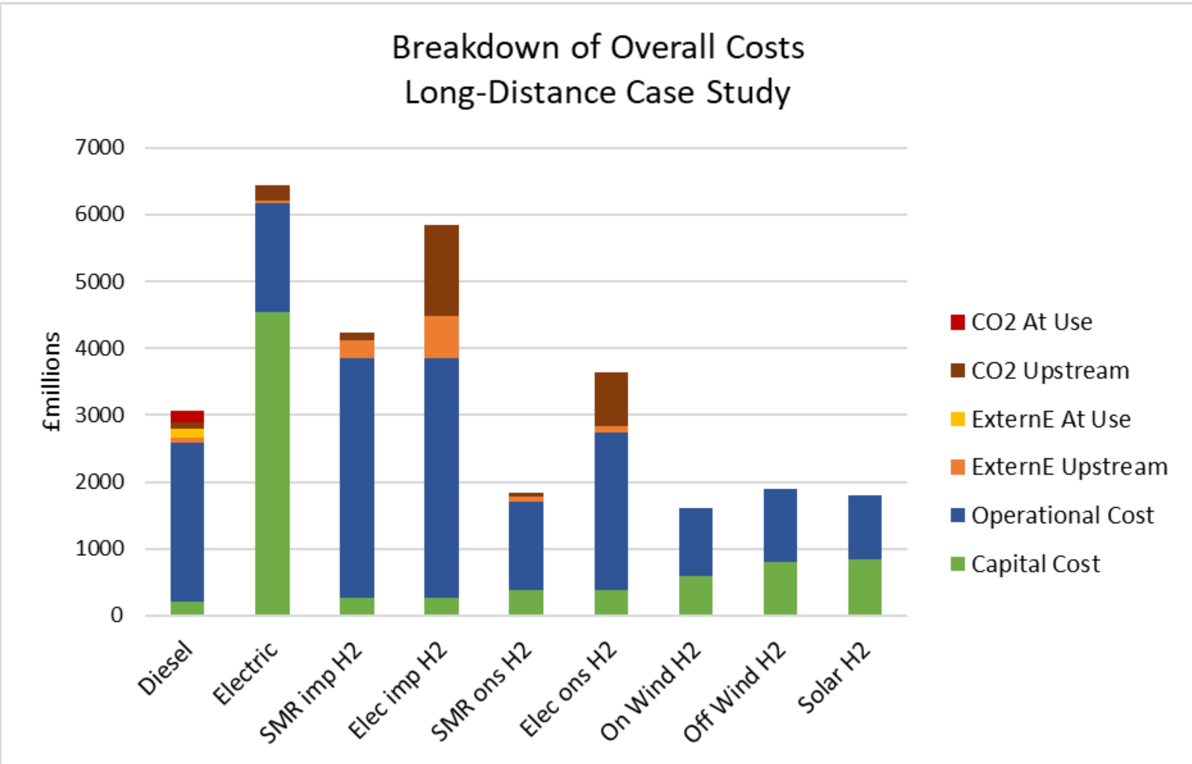

Figure 6.5: Overall Cost analysis, long-distance case study.

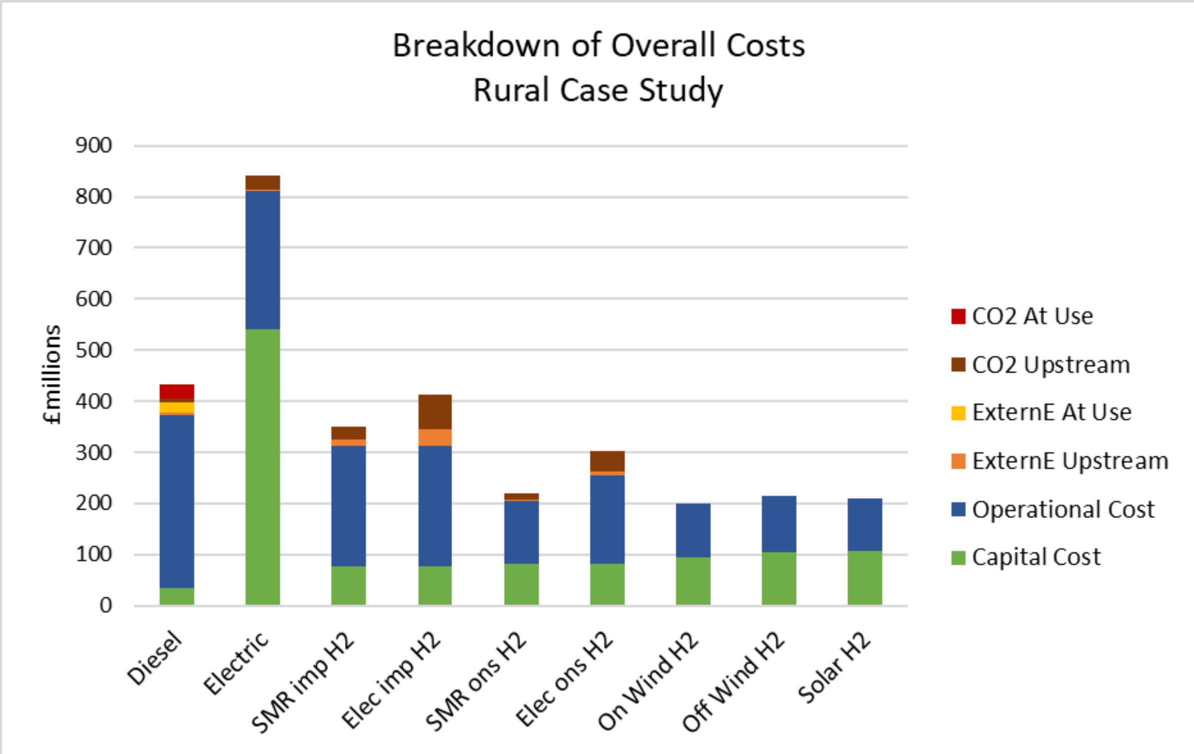

Figure 6.6: Overall Cost analysis, rural case study.

<u>*Treatment of Uncertainty*</u>

The Overall Costs calculated are ranges of values, due to the range of external cost values and the range of electrification cost values. Figures 6.7, 6.8 and 6.9 depict the average Overall Cost values, with error bars to represent the value range. These graphs show that in the Overall Cost comparison, the uncertainty, which mostly arises from evaluation of the external costs, has a relatively low impact. The relative comparison of costs remains the same, even with the presence of uncertainty. The greatest difference stems from electrification of the long-distance case study, and this range is due to the high presence of other services which share the line and could share electrification costs.

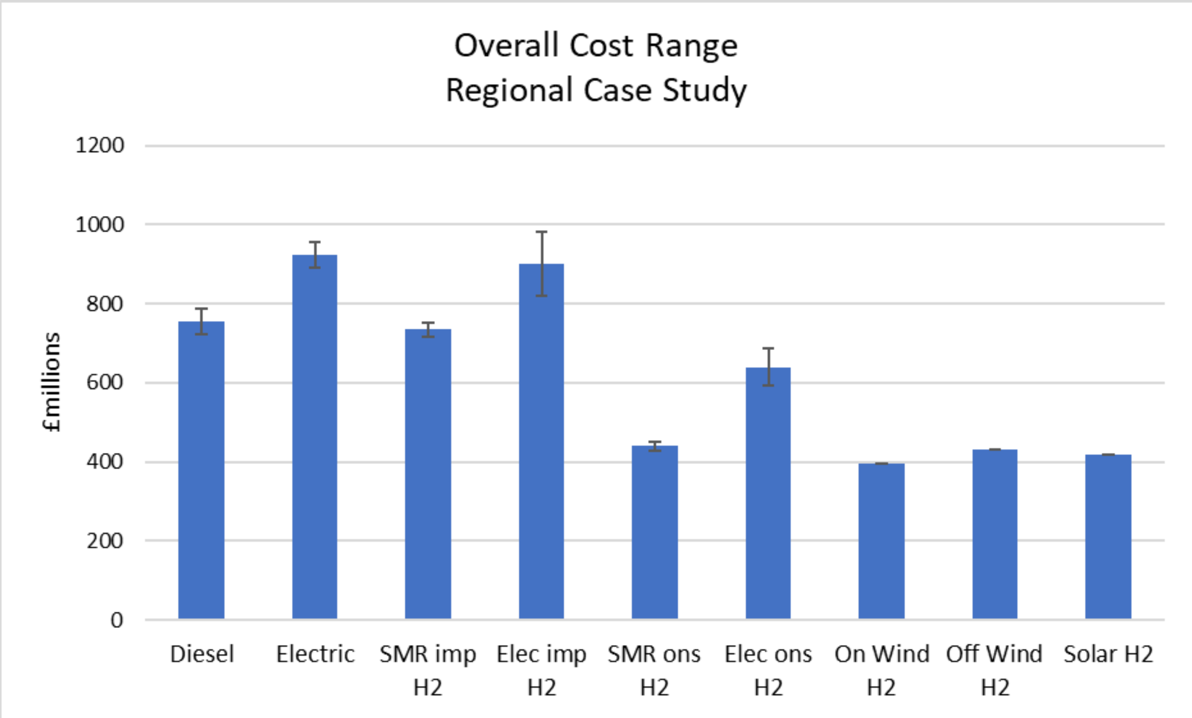

Figure 6.7: Overall Cost range, regional case study.

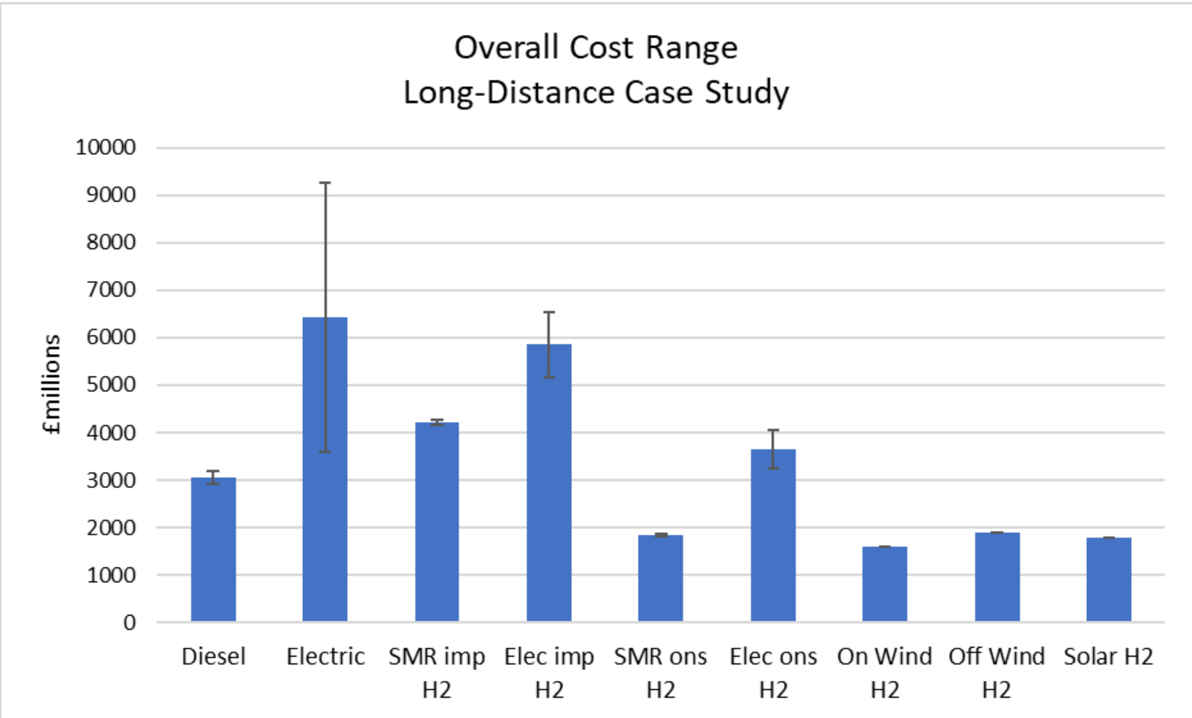

Figure 6.8: Overall Cost range, long-distance case study.

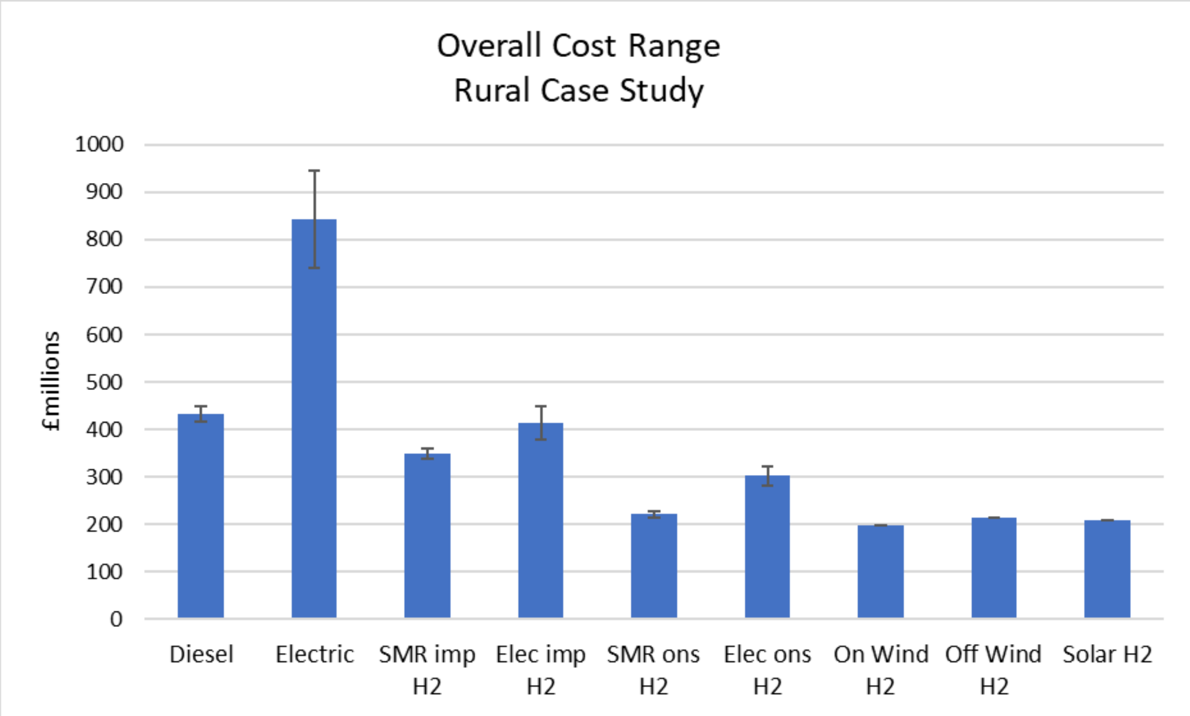

Figure 6.9: Overall Cost range, rural case study.

6.3.1. Comparison of Costs, Based on Travel Distances

Up to this point, the analysis has compared between the options for rail traction within each case study, independently. Translating the results into a common basis allows for a comparison of results between the case studies. The basis used for this comparison is the cost per train-km, as this allows an illustration of costs whilst maintaining the fact that the three routes are intentionally different types of rail service, with different rolling stock and different passenger capacity. Passenger or seat-km are other bases which could be used, however the analysis continues to be focused on the provision of the rail service, rather than the passenger cost perspective. To obtain the results below, the costs were divided by the lifetime km-travelled for each case study route. Tables 6.26, 6.27 and 6.28 give the results on a per train-km basis for external costs, internal costs, and Overall Costs respectively.

Table 6.26: Comparison of external costs on travel distance basis.

(£/train-km)	Regional case study	Long-distance case study	Rural case study
Annual distance travelled (km)	3,829,990	10,401,731	2,302,680
Distance travelled over 30 years (km)	114,899,700	312,051,930	69,080,400
Diesel	0.75 - 1.3	1.1 - 2.0	0.62 - 1.1
Electric	0.17 - 0.44	0.46 - 1.2	0.25 - 0.64
SMR imp H_2	0.46 - 0.79	1.0 - 1.3	0.36 - 0.69
Elec imp H_2	1.37 - 2.78	4.2 - 8.6	0.95 - 2.0
SMR ons H_2	0.18 - 0.37	0.32 - 0.51	0.15 - 0.34
Elec ons H_2	0.54 - 1.4	1.6 - 4.2	0.37 - 0.96
On wind H_2	0	0	0
Off wind H_2	0	0	0
Solar	0	0	0

Table 6.27: Comparison of internal costs on travel distance basis.

(£/train-km)	Regional case study	Long-distance case study	Rural case study
Annual distance travelled (km)	3,829,990	10,401,731	2,302,680
Distance travelled over 30 years (km)	114,899,700	312,051,930	69,080,400
Diesel	5.5	8.3	5.4
Electric	7.6 - 7.9	11.1 - 28.5	10.5 - 13.0
SMR imp H_2	5.8	12.4	4.5
Elec imp H_2	5.8	12.4	4.5
SMR ons H_2	3.6	5.5	3.0
Elec ons H_2	4.6	8.8	3.7
On wind H_2	3.4	5.1	2.9
Off wind H_2	3.7	6.1	3.1
Solar	3.6	5.8	3.0

Table 6.28: Comparison of Overall Costs on travel distance basis.

(£/train-km)	Regional case study	Long-distance case study	Rural case study
Annual distance travelled (km)	3,829,990	10,401,731	2,302,680
Distance travelled over 30 years (km)	114,899,700	312,051,930	69,080,400
Diesel	6.3 - 6.8	9.4 - 10.3	6.0 - 6.5
Electric	7.7 - 8.3	11.6 - 29.7	10.7 - 13.7
SMR imp H_2	6.2 - 6.6	13.4 - 13.7	4.9 - 5.2
Elec imp H_2	7.1 - 8.5	16.5 - 20.9	5.5 - 6.5
SMR ons H_2	3.7 - 3.9	5.8 - 6.0	3.1 - 3.3
Elec ons H_2	5.2 - 6.0	10.4 - 13.0	4.1 - 4.7
On wind H_2	3.4	5.1	2.9
Off wind H_2	3.7	6.1	3.1
Solar	3.6	5.8	3.0

This translation of costs onto a common basis shows that there remains a degree of variation between the three case studies. This can be explained by the fact that the three case studies were chosen specifically to represent as wide a range of type of route as possible, and so there are differences between the case studies other than the distances travelled. For all three sets of cost types, the long-distance case study remains the most costly on a per train-km basis, followed by the regional case study, and the rural case study has the lowest costs. Regardless of traction technology, the long-distance case study requires more powerful rolling stock, which has exponentially higher capital and operational costs, but also carries more passengers. The rural case study is overall cheaper to run than the regional case study, except for electric rail which reflects the higher cost of electrifying a more remote route, though not included in this is the effect of significantly higher passenger numbers on the regional route bringing in a higher income to the operating companies. Evaluating the costs on a per train-km basis demonstrates that the different types of British rail bear different cost levels, although over all of the case studies fuel cell rail remains financially competitive.

6.4. Discussion

This thesis analysis aimed to explore the internal and external dimensions of cost involved in rail traction technology options, and this has been achieved. The options for decarbonising rail have been compared based on emissions, external cost analysis, internal cost analysis, and Overall Costs. Furthermore, these have been compared with incumbent diesel technology. This section introduces some elements which have not been included in the financial analysis, which are further developed in the research limitations in Chapter 8, and the next step of this thesis, that is to discuss how the implications of the research findings can be applied to British rail.

Analysing the capital and operational costs and assembling these into a Lifetime Costing examination, based on the lifetime of rail rolling stock, is a more complete method of analysing the internal costs of rail. The comparison of costs for the different rail technologies returns different results depending on whether the comparison is based on capital costs, the annual operational costs, or the Lifetime Cost. If basing the comparison solely on capital, then diesel rail is significantly lower-cost than the other options for rail traction. However, diesel rail also has one of the highest annual operational costs, which results in diesel being one of the higher-cost options on a Lifetime Cost basis. Conversely, electric rail has one of the lowest running costs, but the high capital outlay means that the annual savings are not enough to make it financially viable, even on a Lifetime Cost basis. The Lifetime Costing also illustrates the importance of choice of hydrogen source in creating a financially viable fuel cell rail system. In the pursuit of lower-cost options for decarbonising rail, Lifetime Costing takes into account all sources of expenditure, and provides a detailed picture of the costs involved over the lifetime of the asset.

The Overall Cost analysis delivers the full picture of costs, internal and external, of rail traction technology options. This analysis enables a comparison between rail options on a fairer cost basis, which takes impacts from emissions into consideration. The initial hypothesis for this analysis was that fuel cell rail would only be financially viable within the Overall Costing results, due to the publicised high costs, but also lower emissions production. The analysis finds that the Overall Costing does not alter the comparison of costs from the Lifetime Cost basis, but it helps to emphasise the relative financial advantage of the lowest cost and lowest emission option, namely fuel cell rail with hydrogen produced using renewable energy (of which onshore wind power is lowest cost). Section 5.4 of Chapter 5 discussed the possibility that external costs are likely to be underestimated. As was shown in Section 6.3, within the Overall Cost analysis, external costs represent approximately 14% of the total for diesel, 4% of the total for electric, and between 8 and 24% of the total for fuel cell with hydrogen options which produce externalities (depending on hydrogen source). This shows that external costs can be a significant proportion of Overall Costs. Although the Overall Cost analysis did not alter the internal cost analysis results in this instance, the analysis still provides a fairer and more detailed picture of the costs of rail provision.

The limitations and further work are discussed in detail in Chapter 8, but there are some specific omissions from the Lifetime and Overall Costing analysis worth mentioning here. Implementing a fuel cell rail system with onsite hydrogen production would necessitate hydrogen storage capacity, especially with the use of intermittent renewable electricity production. There would be a need for excess hydrogen storage capacity to protect against potential supply issues, such as adverse weather conditions for the type of renewable energy installed. It could be beneficial, for the first fuel cell rail projects, to also have onsite SMR production capacity to make use of the national gas grid. This would ensure supply is not disrupted while the inevitable bumps of implementing a new technology are smoothed out, but this would increase the capital costs and produce emissions. Although fuel cell rail has been shown to have lower costs on a lifetime basis, the distribution of capital and operational costs, namely that capital costs are relatively high, can also be a barrier. The fact that fuel cell rail requires greater upfront investment could be seen as a financial risk which could stall its implementation. Although cost is an important factor in decision-making, it is not the only factor, and there may still be financial-related barriers for fuel cell rail to overcome.

The analysis for electric rail used average electrification per single track-km (stk) costs derived from the reported costs of real, planned and completed electrification projects within the UK reported by Butcher (2017a), as detailed in Appendix 4. In 2019, the Rail Industry Association published their Electrification Cost Challenge Report, which aimed to show how electrification costs could be reduced, and demonstrate that recent spiralling of costs (specifically for the Great Western Mainline project) was not indicative of all electrification projects. This report showed that electrification projects can be, and are being, delivered for 33 to 50% lower cost than some reported high-cost projects. The report calls for a rolling programme of electrification, instead of the ‘feast and famine’ programmes to date, to maintain skills, prevent scarcity of equipment and improve efficiency and standardisation of delivery, thus reducing costs. The report addresses the issues of the Great Western Mainline electrification specifically, and gives examples of routes which have been electrified at lower cost per stk. The expectation is that under a long-term, rolling programme of electrification, simple projects should cost £750k-£1.5mi per stk, and more complex projects should cost £1-1.5m per stk. In this analysis, the regional case study uses a cost of £1.6m per stk, the long-distance case study uses a cost of £3.7m per stk (which does include the Great Western Mainline cost within the average, as this would be expected to be a complex project due its distance and terrain), and the rural case uses a cost of £1.9m per stk. In the case where a rolling programme of electrification is indeed implemented, these electrification costs could therefore be expected to be reduced, which would reduce the comparative cost of electric rail and improve its competitiveness on cost grounds. Because this analysis is a 2020 snapshot using 2020 prices, this potential future cost reduction has not been included in the analysis (nor has future reductions in costs associated with fuel cells and hydrogen).

There are also components that have not been included in this analysis, which could further improve the comparative analysis of fuel cell rail costs. Fuel cell trains, like electric trains, are quieter and more comfortable for passengers due to reduced vibrations. Improvements made to passenger comfort on rail could help in the modal shift from private road vehicle transport towards public transport, which can help to reduce overall transport emissions. Furthermore, as fuel cell rail with renewable hydrogen is lower cost than the current diesel rail, implementing this technology could help to reduce rail expenditure. This saving could be used to reduce rail ticket fares, which could further help a model shift towards rail transport. Additionally, removing the need to transport diesel fuel for rail propulsion to train depots, could ease congestion to road and rail freight. This shows that besides external cost impacts, there are other elements of cost which may not be included in conventional financial analysis for decision-making.

6.5. Summary

This chapter presented the results of the analysis of Lifetime and Overall Costs, comparing diesel, electric, and fuel cell rail for the three case study routes. The results show that the least impactful options for rail travel identified in Chapter 5, also have some of the lowest Lifetime costs. This analysis identified the lowest-cost and lowest-emission form of rail transport to be fuel cell rail with hydrogen produced onsite via electrolysis with onshore wind electricity, in all three case studies. This option is financially viable based on internal costs alone, and inclusion of the external costs does not alter the relative comparison of costs. However, there are more elements to implementing a new technology than cost, which are discussed and evaluated in the following chapter.

This costing analysis has shown that fuel cell rail is financially viable, both against the incumbent technology of diesel rail, and against the current best practice for decarbonisation, namely electric rail. Going forward in this thesis, the focus moves on to an examination of the conditions necessary to help fuel cell rail become an option for rail decarbonisation in Britain. The financial case has been presented, so what other elements need to be resolved to make this a reality? The following chapter looks into how technological transitions happen, how the rail system in Britain can move towards decarbonisation, and the practical implications of developing a fuel cell rail system. The findings from the analysis of internal and external costs has led to this direction, due to the fact that this has shown fuel cell rail to be financially viable. The final chapter of this thesis develops the finding that the lowest cost options also produce the lowest emissions, and whether considerations for sustainability and cost can work together in decision-making processes.

Chapter 7: Discussion - Setting the Conditions for Fuel Cell Rail

7.1. Introduction

The previous two chapters established that fuel cell trains are a viable option for British rail, in financial terms as well as in environmental terms. This begs the question as to when and under what conditions it might be expected that fuel cell rail could be adopted. This chapter discusses this question through three topics, namely the theory of diffusion of innovations, the organisation of the British rail system, and the practical implications of fuel cell rail in Britain. This chapter considers the final research objective of examining the implications of the analysis findings for rail decarbonisation in Britain. Firstly, this chapter introduces concepts and theories relevant to the diffusion of innovations, which can be applied to facilitate changes, such as the uptake of a new technology or innovation. More specifically, the rail transition from coal power to diesel power is examined, as an example of a previous successful technological change, which could provide potential insights applicable to the current situation. The second part of this chapter investigates the organisation of British rail, and the role the organisational system has in enabling or preventing technological innovation. The final section analyses the practical implications of fuel cell rail, firstly for the three case study routes, and for the theoretical replacement of all diesel rail on the British network. The elements introduced are then brought together to discuss the deployment of fuel cell trains in a decarbonised rail system.

This chapter investigates the conditions which would facilitate fuel cell rail adoption, including addressing barriers to implementation. Barriers to fuel cell technology in general have been extensively studied in the literature, and cover technological barriers, public acceptance and safety, and economic and political barriers (Hart et al., 2008; Browne et al., 2012; Hardman et al., 2016). This chapter specifically investigates the role of the rail organisational system in causing a disjointed approach to decarbonisation. A lack of clear responsibility can encourage inefficiencies and prevent incentives to innovate (Rail Industry Decarbonisation Taskforce, 2019). Economic and political barriers are generally described in the literature as the most significant and important to overcome (Hart et al., 2008). However, the United Kingdom Government, is 'fully supportive' of fuel cell rail, and it forms part of the Government's long-term reasoning for introducing new bi-mode diesel-electric trains in place of electrification funding (House of Commons Transport Committee, 2018).

Fuel cell trains for the British rail network are still in development. Nonetheless, exploring the necessary conditions for adopting fuel cell rail with a long-term vision is beneficial to the aim of decarbonising rail. The expected lifetime of new rolling stock is 30 years. This means that new diesel trains purchased from now on will still be within their useable lifetime in 2040, when the limit on diesel-only trains comes into force, and even in 2050, which is the deadline for the UK to produce net zero carbon emissions (Department for Transport, 2018a; United Nations Intergovernmental Panel on Climate Change, 2021). A coordinated approach between the entities involved in the rail industry, with common target of decarbonising rail, is needed to improve the efficiency and effectiveness of measures for reducing emissions. Rail is particularly well-suited to the introduction of fuel cells in the transport system, and this offers an opportunity to develop the skills and system required for a decarbonisation of transport more generally. Implementing fuel cells in the rail system furthermore overcomes the infrastructure barriers apparent in private vehicle transport, and implementing fuel cell rail enables to decarbonise routes where electrification is impracticable. The practicalities of implementing fuel cell rail are investigated in this chapter, offering an approach to improving rail sustainability.

7.2. Technological Transition

The analysis of internal and external costs shows that there is a financially viable case for fuel cell rail. The next step in identifying the conditions that would enable a decarbonisation of rail with fuel cell technology, is looking into how technological transitions happen. Firstly, this section looks into concepts pertinent to the transition and diffusion of technological innovations in the literature. This introduces the relevant literature and theories that examine how to make transitions happen, and how these can be used to drive the adoption of technologies to decarbonise public transport in Britain. This section then focuses on the specific case of British rail, investigating the parallel transition of coal rail to diesel in the 1960s, before looking at how this learning can be applied in the pursuit of implementing fuel cell trains. This section aims to investigate the mechanisms through which a technological transition in rail can be implemented.

7.2.1. Diffusion of Innovations

Technologies are constantly innovating and evolving, and being brought into mainstream use. Forming an understanding of the mechanisms for introduction, acceptance, and adoption of new technologies is central to understanding the success of technological development. It is not necessarily sufficient for fuel cell rail to be more cost-effective than the alternatives. As it is a new technology, this comes with other barriers to implementation, which need to be addressed if fuel cell trains are to be adopted. Theories that explain the diffusion of innovations and technical advancements into general use have been extensively studied in the literature. Miller (2017) sets out a detailed procedure for bridging a technological gap and assembles an overview of theories, which have been explored and presented in Table 7.1. Together, these theories identify and characterise different elements involved in a technological transition.

Table 7.1: An overview of theories of technological transitions (Miller, 2017).

Transition Theory	Reference	Theory Focus	Brief Description
Winds of creative destruction model	Abernathy and Clark, 1984	Characterisation of technologies	Categorises innovations based on their influence on established markets and economic impact, and analysis of the implications for competition and existing technology.
Adapting your technological base	Adler and Shenhar, 1990	Characterisation of change	Characterises the magnitude and scope of a change, in order to determine the length of time and depth of change needed.
Adoption population model	Rogers, 1962	Characterisation of adoption populations	Classifies society into five categories based on individuals' propensity to embrace new technology, describing their likelihood and timeframe of adoption, and identifying potential guidance needed to help individuals embrace a new technology.
Crossing the chasm	Moore, 1991	Characterisation of adoption populations and communication	Added to Roger's model, describing the change in communication and marketing strategies needed between the early adoption of a new technology, and its wider dispersion into the population.
Adoption Commitment Curve model	Conner and Patterson, 1982	How individuals learn	Describes the stages of learning for an individual, from the first 'contact' with a new experience through to 'institutionalisation', where it becomes part of the norm. Communication is key to moving through the learning stages.
Satir Change Model	Virginia Satir, date unknown (Miller, 2017)	Transformation system for improvement	Describes the effect of implementing a beneficial change onto performance. In seeking and reaching an improved status quo there is a period of chaos and acceptance which negatively affects performance, but improves with time to a higher performance.

The implementation of a new technology is not a purely financial decision. These theories account for the type of disruption being introduced, the impact of disruption on adopters, and how adopters can be helped through the process of a technological transition. Although the individual is an important entity within these theories, the ideas can be more widely applied to the case of rail. Characterising the type of disruption fuel cell rail is to the rail industry, as well as identifying the correct measures that can be taken, can help deliver widespread acceptance by the adopters. An emphasis on using effective communication to develop an understanding of how the companies and individuals within the rail industry can learn and adapt to this new technology, would help introduction of fuel cell rail. The transition theories highlight the fact that providing the time and space for individuals and companies to learn and adapt, ultimately benefits the introduction of a new technology. There are steps that can be taken before the fuel cell technology is ready for British rail to prepare for the introduction of this new form of rail propulsion technology. By engaging the processes through which to make the technological change, and providing the time for acceptance of the technology, fuel cell rail could be readily adopted on British rail.

The adoption of fuel cells for road vehicles has been studied in the context of adoption of innovations. Hardman (2016) characterised fuel cell vehicles as a 'disruptive innovation' according to Abernathy and Clark's characterisation model (1984). Based on this characterisation, they evaluated the market introduction of fuel cell vehicles as compared to other disruptive innovations, such as the encroachment of battery vehicles into the high-end vehicle market. They recommended a high-end encroachment approach to implementing new fuel cell technology through specialisation, as opposed to pushing for cost-reduction measures aimed at reaching a wider audience. Following this approach thus allows fuel cell technology to emphasise its high-tech advantages over other forms of propulsion, and relies on attracting Rogers' theory (1962) 'innovators' and 'early adopters' to kick-start the adoption of fuel cell vehicles. For rail transport, there is less of a high-end and low-end distinction to train services. However, as fuel cell rail has been shown to be financially viable, this means, contrary to road vehicles, fuel cell rail has already achieved the sought after cost-minimisation. Van Den Hoed (2006) explored the emergence of fuel cells as a 'radical' change within the automotive industry, which is characteristically resistant to innovation. They presented a combination of five 'change factors' to provide sources of radical change:

- New entries, which are characteristically less constrained by vested interests or established processes,
- External shocks or crises, events which disrupt the established norm and create instability,
- Performance of the new technology and demonstrable advantages,
- Market changes, which challenge the established practices or technology, and
- Industry competition, the potential for radical technologies to gain a competitive advantage.

The identified change factors fall into three groups: the attractiveness of a rapidly developing new technology, shocks to the status-quo such as zero-emission vehicles regulations, and competitive profit seeking. These change factors were identified as originating from economic market and technological progression, and government involvement through regulation, and show the means by which radical change could be brought about. Van den Bosch et al. (2004) examined the implementation of a fuel cell transport system on roads and water in Rotterdam, identifying stakeholder issues with the implementation, and creating a roadmap towards energy transition. They concluded that short and medium term projects with achievable targets, based on long-term objectives, can achieve a full system transformation, and that both industry and government need to be pro-actively committed to the long-term vision. One example in their study presents the stages to achieve full decarbonisation of the city bus fleet, first through a decarbonised demonstration fleet, then adding municipal vehicles, then decarbonising 20% of the city bus fleet and eventually decarbonising the complete bus fleet (Van den Bosch et al., 2004).

Fuel cell trains offer the potential to decarbonise rail at a lower financial cost than the alternative of electric. However, fuel cell trains are an innovative technology, which is yet to be proven in service on British rail (although they have been proven in Germany as discussed in Chapter 2, Section 2.3). The costs are not the only factor in enabling rail transition away from diesel. Fuel cell trains are a new innovation in rail, and although from a passenger perspective there is little noticeable change, this creates change elsewhere in the rail service provision. Public transport is a suitable place to implement this new technology, as there is less necessity for widespread public engagement or involvement in the technology diffusion, which is where a technology transition runs the risk of stalling or failing (Moore, 1991). Railways may prove resistant to development, but if there is opportunity to facilitate the change through ‘drop in’ technology, with all requirements provided, this could encourage uptake. The railways have previously accomplished a technological transition, in the move from coal power to diesel power, and this is the subject of the next section.

7.2.2. Lessons in the Transition from Coal to Diesel

Rail in Britain has undergone a substantial shift in propulsion technology before, in the shift from coal (steam) power to diesel. The first diesel powered trains were introduced on British rail in the 1930s by Great Western Railway, though large scale rollout began in 1955, and it took until 1968 for the last steam train to be removed from mainline service. The rail infrastructure was key during the Second World War, but by the end was in a poor state of disrepair, due to high use and low maintenance. At this time, the rail network was owned by the big four (private) rail companies, which were driven into bankruptcy due to the war. In the late 1940s, the railways were brought under government ownership, and as steam trains were cheaper to build, coal was a plentiful supply in Britain, and there were more important things to fund (housing and the National Health Service), around 2,500 new steam locomotives were built between 1948 and 1960, many of which were not in service for their full lifetime (BBC Four Timeshift, 2008). Similarly, new diesel trains brought in today will still be within their serviceable lifetime by the 2040 diesel removal deadline, and even by the 2050 net-zero carbon deadline.

The drive behind the transition to diesel power was threefold. Working on the steam railways was physically challenging, and it was becoming increasingly difficult to find workers. Staff and passengers were losing tolerance to the physical dirtiness of coal, and diesel provided a physically ‘clean’ alternative for rail users and staff alike. Finally, rising availability of road travel was driving competition and a shift away from rail. The 1950s saw a simultaneous shift towards modernisation, and a need to save money. Although electric trains were known to be superior to run, electrification was costly and difficult, as it still is today. Diesel power was cheaper and more straightforward to implement - even initial reliability problems did not stall or halt the national rollout. Diesel trains were 'clean, safe and quiet, easy to drive and maintain, and easier to keep on schedule' (BBC Four Timeshift, 2008). The 1955 Modernisation of the Railways Plan aimed to modernise and reduce costs of running the railways in Britain, with a 15-year schedule and £1.5 billion budget - equivalent to £40 billion today, or the total income for Network Rail over 5 years (Network Rail, 2020c). The Modernisation Plan later included the 'Beeching Cuts', namely elimination of 30% of route mileage, noted in Chapter 2. The Modernisation Plan, and more specifically the 'Beeching Cuts' were and remain a controversial decision. The decision was criticised for being purely based on economics and ignoring the social welfare factors the railways brought, especially to remote communities which suffered the most as a result of the cuts. The issue was that rail could not compete with the car, and leadership at the time saw road transport as the 'way forward', and worth investment. This cutting of the rail network is being revisited now, with improvements to transport decarbonisation requiring greater use of public transport and a shift away from road (Edwards, 2017).

The transition to diesel was first completed in the west of Britain, with the last route converted to diesel being the Liverpool-Carlisle service in 1968. Dieselisation was not a smooth transition, and poor decision-making in the awarding of build contracts meant standardisation of the technology, and any associated economies of scale, would not be achieved. The rate of removal of steam was not always met with the rate of introduction of new diesels trains, and often diesel trains were hurriedly brought online with little testing, resulting in reliability issues. This often resulted in steam trains being brought back online to replace the failed diesel, and many new diesel trains were scrapped within a few years of being built (Physick, 2011). Nonetheless, the technology transition continued, as it was accepted that steam power needed to be replaced. The majority of the technology transition happened in a very short space of time between 1963 and 1968 - and now diesel traction has become the incumbent technology in a new transition (BBC Four Timeshift, 2008).

There are parallels between the shift from steam to diesel and now away from diesel, especially in 2020. When the COVID-19 pandemic lockdown started in the UK in March 2020, travel became limited to key workers only. The Government stepped in at this point to provide funding to keep a minimum number of rail services running and ensure the companies would not go bankrupt - similarly to when the Government assumed responsibility for rail in the late 1940s (Butcher et al., 2020). Fuel cell and electric trains are both ‘clean, safe and quiet, easy to drive and maintain, and easier to keep on schedule’ than diesel - the same advantages diesel held over steam. Although electrification remains costly and difficult, fuel cell trains are cost competitive with diesel. However, when diesel trains were introduced, they had a visible advantage over coal, in being physically cleaner and more pleasant for workers and passengers. Diesel rail provided a means of displacing visible pollution. Besides the costs, the emissions-reduction benefits of fuel cell rail are not necessarily seen by the entities involved in running or using rail, so there is less drive from passengers or workers than with the transition to diesel rail. There is a greater need for policy and regulatory input to bring about the transition, as the push for change rests on the decarbonisation agenda.

Rail developed to meet the need of transporting freight before moving into the transport of passengers. Rail then grew to meet the demand for passenger transport. The transition from coal to diesel was brought about by a need to modernise and improve, in order to attract passengers back from competing road travel. There was a need for rail to keep up with other transport options being offered. The transition needed now is to reduce the emissions associated with the railways, which is also a form of modernisation and of keeping up with other forms of transport, which are also decarbonising. However, in contrast to preceding railway modernisation processes, which were largely reactive, the railways now have the opportunity (although rapidly decreasing with the uptake of electrification on road) to take an active approach to decarbonisation. Railway development is complex, and necessitates collaboration between entities. Furthermore, rail development is characterised by long timeframes. Trains have a 30-year expected lifespan, and it takes two to four years to build a new fleet of rolling stock. Electrification projects can take years to complete. Rail development requires long-term planning, and the processes need to be formulated now, to enable the transition when fuel cell trains come into the mix. The next section aims to develop an understanding of the rail system organisation, in the context of enabling development and adoption of decarbonisation technologies.

7.3. Organisation of the Rail System

Section 7.2 introduced concepts relevant to enabling technology transitions, where the focus for change is on the user and consumer. In the case of rail however, the end user, i.e. the passenger, does not have such a significant role in the success or failure of a new technology. The entities involved in running, funding, and developing rail have a more important role to play. The organisation of the British rail system was introduced in Chapter 2, Section 2.2, with an overview of the different organisations involved. This section focuses on the organisation of British rail in the context of rail development. The aim of this section is to identify areas where the complexity of the organisation of rail may be hindering innovative rail development, and how the complexity can be overcome to help the technology transition. The first part looks into the roles and responsibilities of organisations, particularly with regard to funding and benefitting of rail developments. The second part addresses the creation of opportunities and conditions to enable the adoption of fuel cell rail.

7.3.1. Role and Responsibility in British Rail

British rail is run by a grouping of companies, each responsible for a different element of the railways. The main organisations involved in running the railways are the Train Operating Companies (of which there are 24, excluding Transport for London, airport express services, and Eurostar), the Rolling Stock Operating Companies (of which there are 9), Network Rail, and the Department for Transport and devolved Scottish and Welsh Governments (Office of Rail and Road, 2021b). Furthermore, there is division in transport management between national, regional, and local bodies. Altogether, within the rail industry there is no defined entity with responsibility for rail emissions, creating a lack of incentive or power to reduce the emissions (Hopkinson and Sloman, 2019). The Rail Industry Decarbonisation Taskforce (2019) recommended that the structure of the industry should incentivise net zero, through a clarification of responsibility, and alignment of incentives and risks to maximise rewards and opportunities. Over the entire network, there are 37 distinct organisations within the four different categories of company described (not including regulatory bodies, or rail and passenger groups). Each of these categories of organisations is responsible for a different area of the railways:

- TOCs run the passenger services and franchised stations, provide and collect ticket sales, set ticket prices (within DfT regulation), maintain rolling stock (depending on agreement with ROSCOs, generally smaller maintenance), owe payments to ROSCOs and NR, and disruption payments to passengers.
- ROSCOs own and maintain the rolling stock (depending on agreement with TOCs, generally larger scale maintenance).
- NR own the rail track and all trackside equipment and features (bridges etc.), and are responsible for maintaining and developing all of these, fixing any problems such as signalling failures, and paying compensation to TOCs for disruption caused by infrastructure problems.
- DfT and devolved Governments are responsible for issuing contracts to TOCs to run services, which generally include the rolling stock required from ROSCOs, provide grants to less profitable services to maintain service provision, and provide project funding.

Within the rail system, there is definition of which entities are responsible for which part of daily railway operation. However, there is a disjointedness to the railways, and this is especially visible in railway developments and improvements. Making change on the railways involves coordination and communication between all of the organisations involved, which can be time consuming and cause interruption in developments. For example, May 2018 saw a complete overhaul of train timetabling, affecting 46% of passengers and involving two TOCs. This overhaul, which was meant to improve service provision, in fact caused the disruption and cancellation of thousands of services for weeks following the change. This disarray was due to an accumulation of mistakes made by NR, the TOCs involved, the DfT, and the ORR, and which had not been communicated between entities (ORR, 2018b). The mistakes made showed a lack of coordination between the entities involved. One issue, for example, was that the timetables set out by Network Rail had not accounted for staff retraining on different equipment, or even the number of staff available to provide the services implemented within the TOCs involved (Topham, 2018). Scotland was to undergo a simultaneous major timetabling shift, including the introduction of new rolling stock which formed an integral part of the new timetable. Following delays to the delivery of the new rolling stock, the new timetable introduction was deferred, to allow the companies involved to be adequately prepared for the change. The contrast in Scotland, is that the track and rail services are managed together in a more virtually integrated manner (where partners are treated as one company), which allowed the plans to be altered at short notice (Topham, 2018). This example shows that the fragmentation of rail organisation can prevent flexibility and adaptability to change or issues. This creates complications for rail improvements, which require a high level of coordination between entities in order to be completed and to minimise disruption to passengers.

Organisational fragmentation can have a negative impact on electrification schemes too, and this is also addressed in the Williams-Shapps review, as part of the innovation and modernisation plan for the railways. Rail electrification in England and Wales is currently completed in separate, defined projects. While this is an effective way of breaking down a national task into more manageable projects, it leads to a disjointed approach to electrification. Projects have to compete for funding and equipment, and there is a lost opportunity to improve cost efficiencies from larger scale development. Furthermore, even planned projects (which had won the competed funding) often become reduced or completely cut due to budget constraints and a diversion or reduction of funding. This also leads to a slower and uncoordinated decarbonisation of the rail system (HoC TC, 2018). Again in contrast, Scotland has a rolling programme of electrification to complete smaller route projects one after the other (Transport Scotland, 2020). Network Rail is responsible for the track and infrastructure, including improvements such as electrification, and the Department for Transport provides funding and therefore has authority over electrification schemes. ROSCOs are intended to purchase and supply the trains, however the DfT has also stepped in to procure large orders of rolling stock, and set up 'mini ROSCOs' to fund, own and manage them (Butcher, 2017b). Finally, as the operational benefits of electric rail, such as lower maintenance and reduced fuel costs, appear during use, the TOCs obtain benefits of electric rail without the responsibility for development. The entities responsible for taking on and funding rail developments are different to those receiving the benefits of improvements, meaning that without Government or regulatory involvement there is no incentive for either party to improve.

The timetable disruption led to the Williams Rail Review, and resulting Williams-Shapps White Paper (2021), introduced in Chapter 2. This White Paper sets out to overhaul the organisation of the railways, specifically because of this complexity, and the inefficiencies and problems the organisational fragmentation leads to. The report recommends the implementation of a new public body (Great British Railways), to run, plan, and have responsibility for the rail network - thus creating an overarching guiding mind with responsibility for rail developments and improvements. This, and a rolling programme of electrification, are going to be vital if the Network Rail plan to decarbonise rail through an expansion of electrification to 96% of the UK network is to succeed (NR, 2020d).

The Government, through the DfT, is already highly involved in British rail through funding, regulation, and authority. Without Government involvement, it is likely that electrification schemes would not proceed, so it seems a natural step for the Government to be involved in fuel cell rail roll-out too. The Government has introduced a ban on all diesel-only trains from 2040 (DfT, 2018a). Regulatory instruments could be used further to encourage the adoption of fuel cell rail and create a roadmap towards the elimination of diesel rail. The Rail Industry Decarbonisation Taskforce (2019) investigated the potential to eliminate diesel on rail by 2040, and determined it was possible, but only with much Government input through policy and regulation. They also suggested that the current structural organisation of the rail industry was a hindrance to decarbonisation, and recommended a restructuring with decarbonisation at its core. As the Government is providing funding for the acquisition of electric trains, there is a precedence set, which could cover the financial risk of implementing the new fuel cell rail technology, by providing funding for the acquisition of fuel cell trains. Furthermore, the Government was responsible for the transition from coal to diesel, as at that time the railways were under Government ownership. This also meant there was a greater standardisation of rail. There are currently approximately 20 types (classes) of Diesel Multiple Unit and 40 types (classes) of Electric Multiple Unit trains on the British rail network (DfT, 2018b). The introduction of more standardised trains nationwide, could help towards achieving decarbonisation by simplifying train technology. Regardless of the roles and responsibilities in British rail, the Government has an important role to play in the pursuit of sustainability and creating the conditions for fuel cell rail adoption.

7.3.2. Creating Opportunities for Fuel Cell Rail

Public transport, and rail in particular, offers an opportunity to implement fuel cell technology into the transport system, without the barriers inherent with private road vehicles, such as the lack of a national refuelling infrastructure network. The refuelling infrastructure required for fuel cell rail is also minimal compared to track electrification, and is confined to defined train depots for overnight refuelling. Retraining is only required for a limited number of staff, namely those working on the train refuelling, maintenance, and the drivers (who generally have to retrain when new trains are introduced, regardless of propulsion technology). Furthermore, the financial risks of implementing a new technology can be more easily mitigated by the large companies involved in the rail industry, and through targeted Government funding. The after-effects of the Covid-19 pandemic on rail passengers numbers is yet to be seen, but since 2000, rail passenger numbers have been steadily increasing, and the main problem now is (was) a need for greater capacity (DfT, 2019a). This means there is an opportunity to develop rail, so as to increase capacity and to decarbonise, simultaneously. The fact that passenger numbers are increasing offers assurance of future income. Andersen and Gulbrandsen (2020) reported on the necessity and opportunity for industries to reconfigure and diversify using their existing skills, in order to fit into a sustainable future. Rail is in a good position to decarbonise, and fuel cell rail offers a method to do so that is financially viable, and can be implemented with growth on existing skills.

British rail needs a comprehensive and coordinated approach to decarbonisation. Decarbonisation and improving sustainability are an opportunity to improve the rail system in more ways than reducing pollution. This is the opportunity to increase service provision, improve comfort and journey experience, and possibly reduce ticket prices. Sustainability and environmental protection are not high on the agenda for the British transport system, compared to economic development and congestion reduction (Hopkinson & Sloman, 2019). However, implementing fuel cell rail and developing electric rail where each are best suited, allows the transport system to address economic development, congestion reduction, and emissions reduction simultaneously. The pursuit of sustainability can create economic opportunity. Furthermore, the House of Commons Environmental Audit Committee (2018) reported that climate change needs to be taken into account as a financial risk, and become a part of financial decision making and planning. This means that steps to improve sustainability need to be taken actively, as a reactive approach could lead to financial implications for the entity.

The organisation of rail has been criticised for its fragmentation, short-term thinking, and lack of financial stability in the Williams Rail Review (Butcher & Dempsey, 2020). Furthermore, the Rail Industry Decarbonisation Taskforce (2019) reported that the current system is lacking in definition of responsibilities, which leads to missed opportunities. They recommended that achieving net zero should be at the core of a restructuring of the rail industry structure. Although the Williams Review was not looking into sustainability, the recommendations were to end the current franchising system, to create a single 'guiding mind' to direct the industry, and to increase regional involvement (Butcher & Dempsey, 2020). These recommendations for improving rail aim to simplify the organisation structure, create incentives for improvements, and increase local involvement. This would provide clarification for responsibility, opportunity, and be of benefit to railway development. A simplification of companies, so that there is greater ease of cooperation in developing the railways and enjoying the benefits of improvements, would create a more welcome environment for technological transition. Furthermore, identifying the source of environmental responsibility would enable to apply the ‘polluter pays’ principle, that is targeting the source of decision-making in order to apply an internalisation of external costs (Maibach et al., 2008), so as to ensure the costs do not fall directly onto the passenger. Simplifying the structure of the British rail organisation system, and clarifying development procedures, would support the adoption of fuel cell rail as an option for decarbonisation. An investigation into the practical implications of introducing fuel cells to the British rail system gains relevance at this point.

7.4 A Fuel Cell Rail System in Practice

This section investigates the practical considerations of fuel cell rail deployment, specifically with the option of producing hydrogen onsite from electrolysis using renewable electricity. Implementing fuel cell rail is first considered for the three case study routes, before bringing all the elements of this chapter together to examine the conditions for adoption of fuel cell rail in Britain. The previous section showed that rail is ideally suited to roll out fuel cell technology within the transport sector, as it overcomes some of the barriers which inhibit widespread uptake of fuel cells for private road vehicles. There are two potential barriers to fuel cell rail with renewably-produced hydrogen, namely hydrogen storage and infrastructure space requirements, both of which are explored for the three case studies in this section. A coordinated approach to decarbonising rail, using both fuel cell and electric rail, is further discussed in the final part of this section.

7.4.1. Implementing the Case Studies

The three case studies illustrate the variety of types of rail terrain and service use on rail in Britain. They are all diesel lines, which have not been part of electrification plans, and all pass through Birmingham city centre. The suitability of fuel cell rail deployment varies between the case studies. Firstly, the rural route between Birmingham International and Aberystwyth/Pwllheli is perhaps the best suited candidate for fuel cell rail, due to its relatively low mileage and the unlikelihood of electrification. The route can be subject to track failure from adverse weather, which would be more costly and difficult to repair if the line was electrified. The main depot for this route is at Machynlleth, located nearest to the Aberystwyth terminus, and near the Centre for Alternative Technology, an educational charity focused on research and education on environmental matters (CAT, 2021). This could be a prime location to improve education and public awareness around hydrogen for energy provision. The regional case study between Worcester and Stratford-upon-Avon could also prove a suitable candidate for fuel cell rail. Very little of this route is currently electrified, and it includes tunnels running beneath Birmingham city centre which could prove difficult to electrify. Furthermore, the transition from diesel to fuel cell rail can be made without passenger disruption. The main depot for this line is Tyseley Train Maintenance Depot, conveniently located by the Tyseley Energy Park, a clean energy innovation hub including transport and hydrogen refuelling (TEP, 2020). In contrast, the long-distance route between Penzance and Aberdeen, whilst valuable in the analysis of a higher mileage and higher speed route, would perhaps not be practicable for initial deployment of fuel cell rail. At present, limits to on-board hydrogen storage capacity mean this route would need more trains to provide the current level of service, which increases the costs and has potential knock-on effects for timetabling and rolling stock storage. Furthermore, the current rolling stock on this line is stored in multiple depots, meaning more refuelling and hydrogen infrastructure would be needed, which further increases the costs. Additionally, 40% of this route is already electrified, so it would perhaps be better suited as part of a coordinated electrification programme combined with battery hybrid technology.

Implementing fuel cell rail would require hydrogen storage at depot stations. Hydrogen has a high energy density by weight, but low energy density by volume. This means it is difficult to store, and takes up a large volume, especially when compared to diesel and other liquid fuels, which have high volumetric energy densities. There are three options for storing hydrogen: compressed gas, cryogenic liquid, and metal hydride solid. The most used, easiest and cheapest form of storage is compressed gas, so this taken as the best practice. The on-board storage of hydrogen has been addressed within the analysis of rolling stock numbers in Chapter 6. There is a need for hydrogen storage at the depot stations too, and although fuel storage is already a feature of diesel rail, the space needed for hydrogen storage is likely to be significantly higher. Furthermore, the use of intermittent renewable energy sources to produce the hydrogen, means that extra storage capacity would be a necessity to ensure security of supply. To investigate this additional storage, the volume of hydrogen required to provide three months' supply for the rural case study has been estimated using the ideal gas equation (7.1) (Engineering ToolBox, 2003). Three months was chosen as basis for this calculation, to account, for example, for the three winter months where solar power would not be as productive - although the seasonal disparity of renewable energy production can be overcome with a combined solar and wind system. Table 7.2 presents the results of this three months' of hydrogen storage analysis, which is meant as an illustration of the potentially ideal or maximum storage capacity for a secure and zero-emission fuel cell rail route. To represent the volume of storage, this is compared to an average DMU rail carriage of 240 m^3 (Porterbrook, 2014), though in practice storage would be in large cylindrical storage tanks (BEIS, 2021b).

Ideal Gas Equation

$$V = \frac{mRT}{P} \qquad \dots (7.1)$$

Where

- V is the volume of gas, in m^3
- m is the mass, in kg
- R is the individual gas constant in J/kgK
- T is the temperature, in K
- P is the pressure, in N/m^2

Table 7.2: Three months' hydrogen storage for the rural case study.

Item	Value
Length of time studied	3 months
Annual hydrogen consumption (A5.1)	691,000 kg
Hydrogen consumption over three months	25% - 173,000 kg
Required stored hydrogen	173,000 kg
Individual gas constant for hydrogen (ETB, 2003)	4,124.2 J/kgK
Storage pressure	700 bar (70,000,000 N/m^2)
Storage temperature	15°C (288 K)
Volume stored hydrogen, compressed gas	2,900 m^3
Visual representation	Approx. 12 train carriages

Following on from the storage requirements, fuel cell rail with renewably-produced hydrogen requires additional infrastructure in the form of renewable energy capacity, whether that is solar or wind power. The two largest factors for space requirements with fuel cell rail are hydrogen storage and renewable energy production, so this is investigated for the three case studies. The volume of stored hydrogen is calculated as above, assuming 25% of annual hydrogen consumption is stored at any one time, as a compressed gas at 700 bar pressure. Calculation of the space required for renewable energy production is based on a value of 1 MW per 5 acres for solar power (Solar Trade Association, 2020), and 35 acres per 3 MW turbine for wind (RenewableUK, 2020). The quantities are given a visual representation using a rugby pitch, which is approximately 2.5 acres, and an average DMU rail carriage, which is about 240 m^3 (Porterbrook, 2014). The results are presented in Table 7.3. These estimations show that the storage of hydrogen is reasonable for the regional and rural case studies, requiring about the equivalent of an extra nine and four three-carriage trains, respectively. However, for the long distance case study, the hydrogen storage is equivalent to an extra 80 three-carriage trains, or 48 five-carriage trains, which is larger than the fleet itself. Of the three options for renewable energy, offshore wind is marginally more expensive, however this analysis shows that, in return, less space is needed to provide the same amount of energy for hydrogen production. However, as mentioned previously, a mixture of solar and wind power would ensure an improved security of supply, and these could be combined on the same (onshore) ground and so take up less space.

Table 7.3: Hydrogen storage and renewable energy space for the three case studies.

	Regional Case	Long-distance Case	Rural Case
Annual H_2 consumption (kg) - Appendix 1	1,610,000	13,700,000	691,000
Mass of stored H_2 (kg) - 25% of annual	403,000	3,430,000	173,000
Volume of stored H_2 (m^3) - 25% of annual, 700 bar, 15°C	6,800	58,000	2,900
Visual representation - 240 m^3 train carriages (3-carriage trains)	28 (9 trains)	240 (80 trains)	12 (4 trains)
Solar farm power (MW) - Appendix 4, A4.3	74	628	32
100% solar power (acres) to produce H_2 - 5 acres per 1 MW	370	3,140	160
Visual representation - 2.5 acre rugby pitches	148	1,256	64
Onshore wind farm power (MW) - A4.3	31	268	13
100% onshore wind (acres) to produce H_2 - 35 acres per 3 MW turbine	350 (10 turbines)	3,150 (90 turbines)	140 (4 turbines)
Visual representation - 2.5 acre rugby pitches	140	1,260	56
Offshore wind farm power (MW) - A4.3	21	178	9
100% offshore wind (acres) to produce H_2 - 35 acres per 3 MW turbine	245 (7 turbines)	2,065 (59 turbines)	105 (3 turbines)
Visual representation - 2.5 acre rugby pitches	98	826	42

Adopting a fuel cell rail system would require more space than the current diesel rail. However, this analysis assumes that a dedicated renewable energy farm would be installed for each rail route, which would not necessarily be the case in practice. For example, hydrogen can be produced using excess renewable energy from a decarbonised electricity grid, as part of a coordinated low-emission energy system. It was previously mentioned that a coordinated approach to electrification would improve overall cost efficiencies, and in a similar manner a coordinated approach to decarbonising different parts of the economy - in this instance power production and transport - could benefit the emissions-reduction of both industries. The next section investigates the adoption of fuel cell rail in Britain, including in a coordinated approach to the decarbonisation of rail.

7.4.2. Deployment of Fuel Cell Rail in Britain

This section brings together the previous insights from diffusion of innovations, the organisational system, and the practical elements discussed above. Although the diffusion of innovations theories discussed in Section 7.2 focus mainly on the adoption of a new technology within the general public, there are learnings which can apply more broadly. Decisions are made by companies and the Government, meaning that there may be less resistance to change and quicker retraining and acceptance. Involvement in electrification schemes demonstrates that the Government can also be involved in the implementation of fuel cell rail, so there is opportunity to support the implementation of cleaner and cheaper rail. Initiating a demonstrable pilot project can set up the case for decarbonisation at the core of a system reorganisation, with a combination of technologies for decarbonising rail. A pilot project would not only educate on the technical side of fuel cell rail, but also provide information on the technology acceptance, staff retraining, the best procedure for change, and creating a smooth transition.

Once a fully coordinated programme of transition was put in place, the transition from coal to diesel power took around 15 years. This transition had demonstrable benefits for staff and passengers, and was rolled out by the Government within a publicly-owned system. The benefits to emissions reduction of decarbonising rail, like decarbonising the rest of the economy, are not necessarily directly felt by the passengers or consumers, which is one of the barriers sustainability improvements face. However, there are benefits fuel cell rail can provide over diesel rail, namely reduced noise, improved comfort, and improved reliability (less moving parts), as well as potentially reducing rail fares with a decrease in running costs. These are also the benefits of electrification, but without the negative impacts and cost of electrification infrastructure. Fuel cell rail has demonstrable benefits, which should be taken advantage of, to push for the technological transition. The Alstom Coradia iLint fuel cell train project in Germany has proven successful in deploying fuel cell rail, with the completion of 530 days running and 180,000 km driven from September 2018 (Millikin, 2020). The success and reliability of the iLint has led to further orders and introduction of fuel cell trains on the same line, within other areas in Germany, and branching into several European countries (Zasiadko, 2020b; Van Gompel, 2021). Thirty years of hydrogen supply and refuelling infrastructure, as well as all maintenance, was included in the Alstom package for the project, leading to a straightforward, low risk, instant change of technology (Railway Technology, 2019). This reduces the risk taken by rail ownership and operating companies, and enables retraining to occur during the switchover. Establishing features which can simplify change is a successful technique for enabling the technology transition to fuel cell rail.

The representational case studies showed that regardless of the route, fuel cell rail is more cost-effective than electric rail for decarbonisation, within the boundaries of the analysis (Chapter 4, 4.1). This would indicate that the optimal solution to eliminate diesel power from the railways could be to replace all current diesel power with fuel cell rail, prompting a brief investigation into whether this would be feasible, with regards to hydrogen storage and renewable energy production capacity. On the British rail network, around 500 million train-km are travelled annually, and 40%, or 200 million train-km, of this is diesel powered (Goddard, 2018). Altogether, the three case studies require just under 16,000 tonnes of hydrogen per year, and make up 3.33% of the total British network distance travelled, or 8.27% of diesel distance travelled (Appendix A5.1). The hydrogen production and storage requirements, and renewable energy capacity, have been calculated based on these numbers, as in Table 7.3, with the results presented in Table 7.4. For this case, the renewable electricity has been calculated based on equal third shares between solar, onshore wind, and offshore wind. A combination of renewable energy sources would be optimal for security of supply and spreading electricity production over differing weather conditions. Thus, the results for renewable energy production are added together in these results, not separate cases as in Table 7.3. It has also been assumed solar and onshore wind can be produced at the same location. In practice, however, the UK's generation mix has a higher proportion of wind generation than solar (17.7% wind and 3.9% solar for the year 2020-21, Morley, 2021) - but the rail industry has potential to make use of its building spaces to become a solar generator, on top of the assumed combined offshore wind and solar arrays. The fact that meteorological conditions favour wind in the UK is accounted for within the load factors, which illustrates the expected annual production from the installed capacity.

Table 7.4: Hydrogen storage and renewable energy for the British rail network.

Item	Value
Annual H_2 consumption for the three case studies	16,000 t
Three cases studies proportion of total diesel traction	8.27%
Annual H_2 consumption if all diesel converted to fuel cell	193,000 t
Maintained H_2 storage (25% of annual consumption)	48,000 t
Number of train depots for H_2 storage (ORR, 2021a)	100
National H_2 storage volume (25% of annual consumption)	814,000 m^3
H_2 storage at each depot (compressed gas, 700 bar)	480 t / 8,140 m^3
Visual representation - 240 m^3 train carriages (3-carriage trains)	34 (11)
Electrolysis power requirement	1,800 MW
1/3 solar farm power (11.3% load factor)	5,300 MW
1/3 onshore wind farm power (26.4% load factor)	2,270 MW
1/3 offshore wind farm power (40.1% load factor)	1,500 MW
Onshore space for solar + onshore wind (turbines)	26,500 acres (757)
Offshore space for offshore wind (turbines)	17,500 acres (500)

To illustrate the results, 5,300 MW is approximately 40% of the UK's solar photovoltaic installed capacity in 2018 (BEIS, 2021). For onshore wind, 2,270 MW is approximately 15% of the UK's onshore wind installed capacity, and for offshore wind, 1,500 MW is approximately 17% of the UK's installed offshore wind capacity in 2018 (BEIS, 2021). The UK's largest onshore windfarm has 140 3 MW wind turbines, and largest offshore windfarm has 175 turbines, where just over 750 and 500 respectively would be needed here - though they do not have to be all in the same place (RenewableUK, 2020). 26,500 acres of combined wind and solar is approximately 0.05% of the UK's agricultural land - although wind and solar do not require particularly agricultural land, and they can share the land for pasture (STA, 2020). At each depot, the volume of hydrogen storage is equivalent to about 34 train carriages, or 11 to 12 three-carriage trains, which is not a significant volume in comparison to the number of trains present on the network.

As the analysis above shows, although fuel cell rail with renewably-produced hydrogen was estimated as being financially viable, converting all remaining diesel rail to clean hydrogen requires a significant amount of storage capacity and renewable energy capacity. Decarbonisation needs a coordinated approach with a common goal, so that the optimum mix of technology can be reached. Electrification still has advantages over fuel cell rail, especially in more densely used and high-speed rail. At present however, electric traction is not emission-free: the UK electricity grid in 2018 consisted of 40% natural gas, 29% renewables, 21% nuclear, and 10% oil and coal (BEIS, 2019b). This produced around 100 MtCO_2e for the year 2018, although as figure 7.1 shows, emissions from the UK grid are rapidly reducing (BEIS, 2020a).

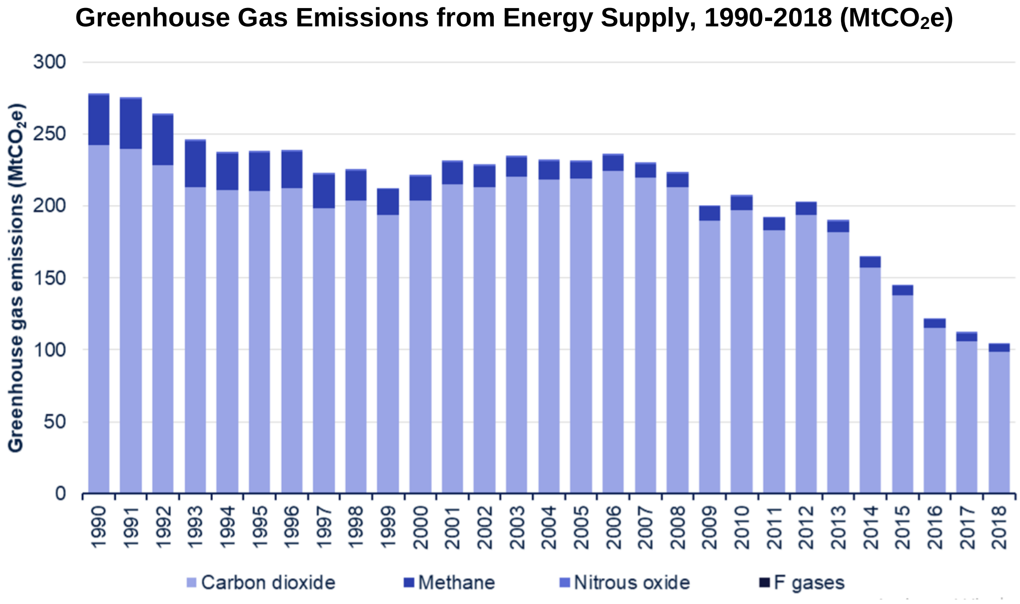

Figure 7.1: Greenhouse gas emissions from UK energy supply (BEIS, 2020a).

However, decarbonisation of the electricity grid cannot be fully achieved without large-scale energy storage. Hydrogen is a means of large-scale energy storage, especially for excess renewable electricity. There is an opportunity to create a coordinated electric-fuel cell rail system, which makes the best use of zero-carbon electricity and stores the excess as hydrogen for routes which cannot be easily electrified. This opportunity needs a coordinated and long-term approach, considering every element of the rail system together in the ultimate goal of improving sustainability. An overall approach could improve the efficiency and end results of the technology transition, and the long-term nature of rail, with rolling stock lifetimes of 30 years or more, means a long-term vision is a necessity.

This analysis is only meant as a quick illustration of broadening the learnings from this thesis into the wider GB rail system, even so analysing the rail system as a whole, as opposed to individual case studies, requires a different, system-wide, approach. The UK Energy Research Centre, for example, has produced a Transport Energy Air Pollution

Model (TEAM), which has been designed to investigate energy consumption and air pollution emissions from the transport system, with inclusion of technical efficiency, mode choice, pollutant content, lifestyle choices, and socio-economic factors (Anable et al., 2019). Logan et al. (2020) used this model to determine passenger demand and service provision. This system-level model would be recommended for system-level change modelling. Making change at a route level, without considering the wider transport system implications, would go against the idea of creating a sustainable system, wherein internal and external factors are taken into account. The emphasis is on a coordinated approach, which necessitates system-level modelling and analysis to determine the optimal mix of technologies to decarbonise transport as a whole, which is why informed Government involvement is important in affecting system-wide, coordinated, change.

7.5. Summary

This chapter explored some of the conditions necessary, beyond economic and environmental advantage, to enable a technological transition in rail. The discussion followed this direction after the analysis showed fuel cell rail to be financially and environmentally viable, especially when fuelled with hydrogen produced via electrolysis using renewable electricity. This chapter therefore introduced theoretical procedures for the diffusion of innovations and management of disruption brought on by technological change or innovation. The transition from coal to diesel rail was reviewed as an example of successful change in rail. The impacts and effects of the rail organisational system were presented, along with opportunities for change. Practical elements of introducing fuel cell rail to the three case study routes, and to replace diesel on the whole British network, were analysed. Finally, this chapter showed the importance of a coordinated and long-term approach with common aim, in order to successfully decarbonise rail.

Rail offers an advantageous situation to rollout fuel cells into the transport sector, as it is easier to implement the infrastructure and retraining necessary than private road vehicles. The theories introduced around diffusion of innovations largely address the disruption and resistance to change of individuals, which can slow or prevent the progress of a new technology. In replacing diesel rail with fuel cell, the passengers would not see the impact of rail technology change other than improved comfort, so there is less source of resistance to change from the end-consumer. There is an opportunity to create the conditions for adoption of fuel cell rail onto the British rail network.

The complexity of the organisational system leads to a lack of incentive for large-scale emissions reduction in rail. However, Government involvement in electrification schemes means there is a precedent set for Government involvement in fuel cell rollout too, which can facilitate the transition. The Government has already placed a 2040 deadline on the removal of diesel-only trains, and used the development of fuel cell technology as a justification for the introduction of diesel-electric bi-mode rail, stating the diesel engine can later be replaced by fuel cell technology (DfT, 2018a). This chapter shows that while fuel cell rail is perhaps not intended as the perfect solution, there are opportunities for its implementation to prove beneficial.

The final part of this chapter recommended a coordinated and long-term approach to decarbonising the rail system, which includes fuel cells with renewably-produced hydrogen. This is a whole system strategic change, with common goal to reduce or even eliminate emissions from transport. There is recognition within the rail industry that the complex system of organisation prevents creative developments and opportunities, and this can be tackled simultaneously to this strategic change. The financial case for fuel cell rail is there, and the discussion has now opened up to bring about the conditions necessary for the technological transition. The next and final chapter of this thesis brings together all the findings and discussions, and considers the wider issue of making decisions, based on cost and sustainability factors.

Chapter 8: Summary and Implications for Decision-Making

8.1. Introduction

This chapter assembles and concludes the research undertaken in this thesis, as well as using the findings to instigate a wider discussion on decision-making based on cost and sustainability factors. This chapter first summarises the research findings, with a review of the data analysis and topics discussed in Chapters 5, 6 and 7. The next section develops the fact that this thesis found that the lowest cost option for rail traction also produces the lowest emissions, and explores the pursuit of cost and emissions reduction as a common goal in decision-making. Finally, this chapter evaluates some of the limitations of this thesis, and develops areas for further research.

This thesis focused on the production and reduction of emissions as a mechanism to measure and improve the sustainability of rail. Including sustainable elements, such as a focus on emissions reduction, at the core of decision-making processes, ensures the impacts of decisions can be taken into account. Monetisation of external costs has been shown to be a method of accounting for impacts into cost-based decision-making in Chapters 3 and 5. Chapter 7 explored decision-making factors in the context of implementing fuel cell technology on the British rail network. This chapter now focuses on decision-making in the wider context of improving sustainability, and more specifically on the topic of forming decision-making factors based on cost and sustainability considerations in parallel. This discussion hopes to bring together the idea that reducing emissions can be financially viable, and that improving sustainability can be an economic and development opportunity for industry.

This thesis has shown that in the context of rail, the option for rail traction with the lowest emissions is also financially viable, on a Lifetime Cost basis. However, the imbalance between the higher capital and lower operational costs remains a disadvantage when decisions remain highly biased towards capital costs (Wu et al., 2015). Furthermore, decisions are not solely based on financial advantage. Nonetheless, this chapter investigates whether sustainable options are now becoming more cost-effective, and whether the pursuit of cost reduction for more sustainable technologies is becoming unnecessary. The system could be on the cusp of a change, where sustainable options are becoming cheaper than conventional, which could lead to a snowballing of implementation and emissions reduction.

8.2. Research Findings

This section assembles and summarises the findings from the research analysis. The aim of this thesis was to explore the internal and external dimensions of cost of options for decarbonising British rail. The objectives as detailed in Chapter 1 were:

- To select representative case studies for examination,
- To evaluate rail emissions for diesel, electric and fuel cell rail,
- To evaluate the impact of rail emissions through external cost analysis for diesel, electric and fuel cell rail,
- To evaluate the internal costs of diesel, electric and fuel cell rail,
- To examine the Overall Costs of diesel, electric and fuel cell rail, and

- To examine the implications of the findings for rail decarbonisation in Britain.

The objectives have been met through the development of this thesis. The three case studies of a regional route, long-distance route, and rural route, illustrate the variety of rail terrain and service use on British rail. The case study routes all pass through Birmingham city centre, which has also been considered in the analysis, to additionally illustrate the impact of rail in an urban environment. The cases have been used to examine the emissions and costs of British rail, with the current rail propulsion technology, and with the potential for less polluting traction technology. Decarbonisation of British rail is the underlying theme to the research, and the implication of the findings is discussed in the context of decarbonising rail. In working through the objectives of this study, the aim is addressed, and the internal and external dimensions of cost are explored.

To contextualise the analysis of rail traction technologies, emissions and costs, the literature research developed an understanding of the British rail system, and the impacts of rail within the context of transport and climate change emissions. The second portion of the literature review focused on concepts for the analysis, and presented Full Cost Accounting as the concept on which the analysis procedure was based on. The methodological process and analysis results for evaluating rail traction options were split into two parts: the analysis and monetisation of emissions and impacts, and the analysis of internal costs. The results of the analysis showed a favourable case for fuel cell rail, both on emissions and cost grounds, which led the discussion towards exploring other considerations for the adoption of fuel cells in the British rail system. This discussion explored concepts relevant to technological transition theory, and explored the practical implications of fuel cell rail, including the role of rail industry organisations and

Government involvement. The next two sections focus on the findings of the analysis in Chapters 5 and 6. First the findings of the analysis of emissions and their impacts are reviewed, then the findings from the analysis of costs.

8.2.1. Rail Emissions and External Costs

The first part of the analysis evaluated the emissions from rail, for the three case studies, and for rail provision within Birmingham city centre. For Birmingham, the emissions were calculated based on the current mix of diesel and electric trains. The three case studies were used to evaluate the potential for fuel cell rail, so the emissions were calculated for the current diesel provision (upstream fuel production and downstream at-use), replacement with electric (upstream grid electricity production), or replacement with fuel cell rail (upstream hydrogen production). As the emissions of fuel cell rail depend on the source of hydrogen, seven options for hydrogen production were considered:

- Imported hydrogen produced from steam methane reforming (SMR imp)
- Imported hydrogen produced from electrolysis with EU average grid electricity (Elec imp)
- Onsite production via steam methane reforming, with UK gas grid methane (SMR ons)
- Onsite production via electrolysis, with UK grid electricity (Elec ons)
- Onsite production via electrolysis, with solar power (solar)
- Onsite production via electrolysis, with onshore wind power (on wind)
- Onsite production via electrolysis, with offshore wind power (off wind)

Table 8.1 presents the summary of the annual emissions analysis results for Birmingham (Chapter 5, Section 5.2.1), and Tables 8.2, 8.3 and 8.4 present the summary of the emissions analysis results for the three case studies over the defined 30 year lifetime (Chapter 5, Section 5.3.1). REN refers to hydrogen produced with the three options for renewable electricity, with no emissions.

Table 8.1: Summary of emissions analysis for Birmingham, single year.

Pollutant (t/y)	Diesel Rail	Electric Rail	Annual Total
Annual distance travelled (train-km)	1,610,000	1,570,000	3,170,000
CO_2e/CO_2	6,970	4,320	11,290
SO_2	15.1	4.85	20.0
VOCs	6.87	3.54	10.4
CO	7.90	0.693	8.59
PM_{10}	3.29	0.385	3.68
NO_x	64.5	5.93	70.4

Table 8.2: Summary of emissions analysis for the regional case study, 30 year lifetime.

Emissions (t)	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
CO_2e/CO_2	436,000	212,000	264,000	1,120,000	155,000	655,000	0
SO_2	931	106	1,040	3,430	99.6	327	0
VOCs	433	22.6	125	122	72.2	70	0
CO	352	67.9	/	/	/	210	0
PM_{10}	204	33.9	201	349	60.5	105	0
NO_x	4,040	309	1,160	1,470	752	956	0

/ refers to a lack of data.

Table 8.3: Summary of emissions analysis for the long-distance case study, 30 year lifetime.

Emissions (t)	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
CO_2e/CO_2	1,870,000	1,580,000	718,000	9,510,000	420,000	5,560,000	0
SO_2	5,390	787	8,870	29,100	845	2,770	0
VOCs	1,880	169	1,060	1,030	613	594	0
CO	3,920	506	/	/	/	1,780	0
PM_{10}	1,130	253	1,710	2,970	514	891	0
NO_x	16,400	2,310	9,840	12,500	6,380	8,120	0

/ refers to a lack of data.

Table 8.4: Summary of emissions analysis for the rural case study, 30 year lifetime.

Emissions (t)	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
CO_2e/CO_2	239,000	188,000	159,000	481,000	92,900	281,000	0
SO_2	515	94	448	1,470	42.8	140	0
VOCs	235	20.1	53.8	52.2	31.0	30.0	0
CO	193	60.3	/	/	/	90.1	0
PM_{10}	110	30.1	86.4	150	26	45.1	0
NO_x	2,210	275	497	633	323	411	0

/ refers to a lack of data.

The next stage of analysis was to evaluate the external costs of emissions. The localised environmental and health impacts of the calculated emissions were monetised following two methodologies, ExternE and the Handbook on External Costs of Transport (HECT). The global impacts of CO_2 emissions were calculated separately using UK Government Department for Transport data, which gave a range of values for CO_2 costing. A summary of the results of annual external cost analysis for Birmingham (Chapter 5, Section 5.2.2) and the three case studies over the 30 year lifetime (Chapter 5, Section 5.3.2) are presented in Tables 8.5 to 8.8.

Table 8.5: Summary of external cost analysis for Birmingham, single year.

Monetisation (£)	Diesel Rail	Electric Rail	Total
ExternE	766,000	110,000	876,000
HECT	3,180,000	1,770,000	4,950,000
CO_2e	264,000 - 783,000	164,000 - 486,000	427,000 - 1,270,000
Total Range	1,030,000 - 3,960,000	274,000 - 2,260,000	1,300,000 - 6,220,000

Table 8.6: Summary of external cost analysis for the regional case study, 30 year lifetime.

£millions	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
ExternE	54.6	4.66	33.4	76.1	9.40	14.4	0
HECT	227	130	/	/	/	/	0
CO_2e	31.6 - 94.7	15.3 - 46	19.1 - 57.4	81 - 243	11.2 - 33.6	47.4 - 142	0
ExternE + CO_2e	86.2 - 149	20 - 50.7	52.5 - 90.8	157 - 319	20.6 - 43	61.8 - 156	0

/ refers to a lack of data.

Table 8.7: Summary of external cost analysis for the long-distance case study, 30 year lifetime.

£millions	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
ExternE	209	30.9	262	616	69.0	109	0
HECT	511	135	/	/	/	/	0
CO_2e	135 - 405	114 - 343	51.9 - 156	688 - 2,060	30.4 - 91.1	402 - 1,210	0
ExternE + CO_2e	344 - 614	145 - 374	314 - 418	1,300 - 2,670	99.4 - 160	511 - 1,320	0

/ refers to a lack of data.

Table 8.8: Summary of external cost analysis for the rural case study, 30 year lifetime.

£millions	Diesel	Electric	Fuel Cell				
			SMR imp	Elec imp	SMR ons	Elec ons	REN
ExternE	25.7	3.61	13.1	30.9	3.42	5.40	0
HECT	61.3	20.1	/	/	/	/	0
CO_2e	17.4 - 51.9	13.6 - 40.8	411.5 - 34.5	34.8 - 104	6.72 - 20.2	20.3 - 61.1	0
ExternE + CO_2e	43.1 - 77.6	17.2 - 44.4	24.6 - 47.6	65.7 - 135	10.1 - 23.6	25.7 - 66.5	0

/ refers to a lack of data.

8.2.2. Rail Costs

The second part of the analysis evaluated the internal costs, that is the capital and operational costs, of rail traction options for the three case studies, over a 30-year lifetime. The internal and external costs were then assembled to form the Overall Costs. Based on the internal Lifetime Costs alone, the lowest cost options for rail traction were calculated to be fuel cell rail with hydrogen produced onsite, from electrolysis using renewable energy, or from SMR, and for all three case studies. Analysing the Overall Costs consolidated this finding, as fuel cell rail with renewably-produced hydrogen is the only option which does not cause external costs. Results from the internal and Overall Cost analyses for the 30 year lifetime are summarised in Tables 8.9, 8.10 and 8.11.

Table 8.9: Summary of cost analysis for the regional case study, 30 year lifetime.

Costs £mill	Diesel	Electric	Fuel Cell						
			SMR imp	Elec imp	SMR ons	Elec ons	Solar	On wind	Off wind
Cap	59.4	545 - 579	182	182	195	195	251	222	245
Op	577	326	481	481	214	335	168	174	186
Int	637	870 - 904	662	662	409	530	419	396	431
Ext	86.2 - 149	20 - 50.7	52.5 - 90.8	157 - 319	20.6 - 43	61.8 - 156	0	0	0
Overall	723 - 786	890 - 955	715 - 753	819 - 981	430 - 452	592 - 686	419	396	431

Table 8.10: Summary of cost analysis for the long-distance case study, 30 year lifetime.

Costs £mill	Diesel	Electric	Fuel Cell						
			SMR imp	Elec imp	SMR ons	Elec ons	Solar	On wind	Off wind
Cap	216	1,820 - 7,250	265	265	375	376	847	599	797
Op	2,370	1,640	3,590	3,590	1,330	2,350	948	999	1,099
Int	2,590	3,460 - 8,890	3,860	3,860	1,710	2,730	1,795	1,598	1,896
Ext	344 - 614	145 - 374	314 - 418	1,300 - 2,670	99.4 - 160	511 - 1,320	0	0	0
Overall	2,930 - 3,200	3,610 - 9,260	4,170 - 4,280	5,160 - 6,530	1,810 - 1,870	3,240 - 4,050	1,795	1,598	1,896

Table 8.11: Summary of cost analysis for the rural case study, 30 year lifetime.

Costs £mill	Diesel	Electric	Fuel Cell						
			SMR imp	Elec imp	SMR ons	Elec ons	Solar	On wind	Off wind
Cap	34	452 - 630	76.8	76.8	82.4	82.5	106	93.8	104
Op	338	271	236	236	122	173	102	105	110
Int	372	722 - 900	313	313	204	256	208	199	214
Ext	43.1 - 77.6	17.2 - 44.4	24.6 - 47.6	65.7 - 135	10.1 - 23.6	25.7 - 66.5	0	0	0
Overall	415 - 450	739 - 944	338 - 361	379 - 448	214 - 228	282 - 323	208	199	214

It was not initially hypothesised that fuel cell rail would be a competitive, financially viable option, particularly in comparison to the incumbent diesel rail. Moreover, the financially viable fuel cell option is with hydrogen that is produced using renewable energy, and so is the lowest polluting of all the options considered. This meant that examining the implications of the results for British rail decarbonisation necessitated an approach which was not based in creating conditions to make fuel cell rail financially viable, as the case was already in place. This created an opportunity to explore other areas relevant to the implementation of a new technology, namely the concepts and theories of technological transitions. The adoption of a new technology is not a purely cost-based decision, and technological transition concepts give insights into how transitions happen and how to manage disruption brought about by change. Government involvement is likely to be key in the implementation of fuel cell rail, and a reorganisation of the rail system structure should put sustainability at its core.

This research explored the internal and external dimensions of cost of rail in Britain, within the underlining theme of decarbonisation. The analysis shows that fuel cell rail is a financially and environmentally viable option to decarbonise British rail. The favourable outcome for fuel cell rail led to the exploration of the practicalities of fuel cell rail and the conditions necessary for implementation. Overall, this shows that there is an opportunity and a place for fuel cells as part of a decarbonised rail system in Britain. In Chapter 1, the fact that cost is an important factor in railway decision-making was emphasised, however this analysis has shown that in the situation studied, evaluating cost and emissions-reduction led to the same option for rail traction. This leads to the question of whether cost and emissions-reduction factors can be considered together in the context of decision-making.

8.3. Sustainable Decision-Making

The underlying theme behind this research is the decarbonisation of rail, as part of wider efforts to decarbonise transport in the scheme of aiming for net zero emissions by 2050 (United Nations Intergovernmental Panel on Climate Change, 2021). To reduce and eliminate emissions, in order to address the climate crisis and global impact of human activity, it is necessary for sustainability to become a factor in decision-making. The research undertaken in this thesis showed that for the specific topic investigated, the option which produces the least emissions also has the lowest cost. Thus, the first part of this section discusses the idea that cost and sustainability do not have to be competing factors in decision-making. The second part initiates discussion into how to stimulate sustainable decision-making. Instituting sustainability factors at the core of decision-making is key to reducing emissions and improving sustainability, rather than regarding it as an add-on or afterthought, purely to meet targets.

8.3.1 Reducing Costs and Emissions

This analysis showed that for the very specific case of traction technology on British rail, the lowest emissions and lowest cost options are the same. This is not necessarily a unique position, as sustainable technologies are becoming more financially viable with increased uptake and savings of scale, regulation changes, and improved development and experience. Research from the United States Department of Energy shows that between 2006 and 2018 the price of Polymer Electrolyte Membrane (PEM) fuel cells has decreased by 60% through developments such as a reduction in platinum use, and is projected to reduce a further 20% with an increase in production rates (Wilson et al., 2017). The fuel cell production company, Ballard, shows that the cost of fuel cell vehicles has decreased by 65% between 2010 and 2020, and that each generation of fuel cell they produce, costs are cut by a third. They predict fuel cell vehicles to become cost competitive with battery and diesel by 2030 (Pocard, 2020).

Renewable energy is ahead of fuel cells in this regard, showing the impact of development, increase in production, and a maturing of the technology on pricing. In 2019, globally, 56% of all new large-scale renewable power generation provided electricity at a lower cost than the cheapest new fossil-fuelled option. 75% of wind projects and 40% of solar photovoltaic (PV) projects were cheaper than the cheapest fossil option. Solar PV power has had the greatest cost reduction of the renewable technologies, with utility-scale projects dropping in cost by 82% between 2010 and 2019. Furthermore, these costs are still reducing, to the point that new onshore wind and solar PV projects are becoming cost competitive with *installed* coal-fired power (International Renewable Energy Agency, 2020). Another example, studies comparing battery electric vehicles (BEV) have been finding on a Lifetime Cost basis, BEV can be cheaper than their petrol, diesel and hybrid counterparts - though generally, as BEV have a higher upfront cost but lower running costs, the economic viability depends on the lifetime mileage (Offer et al., 2010; Wu et al., 2015). This is a common trait among more sustainable technologies, whereby the higher capital costs are offset by lower running costs on a lifetime basis. This shows the importance of Lifetime Cost analysis to determine the actual financial viability. However, these cost analyses do not include the fact that many polluting technologies are incumbently in place, meaning there is an additional cost barrier to overcome. At the end of life of incumbent technologies however, sustainable options could be financially viable replacements and should be considered alongside other options, even aside from the need to reduce emissions. The cost-competitiveness of sustainable technologies is only going to increase with increased development, experience and roll-out, leading to a spiralling of sustainability improvements and emissions reduction.

Despite lower Lifetime Costs, the higher capital cost remains an issue in the cost competitiveness of sustainable technology. In the particular example of fuel cell rail, the capital cost is higher than the incumbent diesel, but also lower than the alternative of electrification, so this may not be expected to be a significant barrier. In the case of battery electric vehicles for example, even if the Lifetime Cost is less, the higher upfront cost of the vehicle, along with the perceived risk of the higher upfront cost and still relatively new technology, are a significant barrier to adoption (Dumortier et al., 2014). The higher upfront cost makes adopting battery vehicles unfeasible for many consumers, meaning they cannot take advantage of the opportunity to save costs and reduce emissions that battery vehicles can offer. Improved and increased public transport provision could help to reach those consumers that want to reduce their emissions footprint but cannot afford some of the higher capital necessary. In industry, there is an opportunity to integrate sustainability measures at the core of project and organisation development. The ability to adapt to change and proactively seek opportunities makes strong businesses. Aiming for environmental sustainability in business is becoming the pursuit of economic sustainability, as the economic climate and markets are changing (House of Commons Environmental Audit Committee, 2018). Although fossil fuel is the established energy resource, price volatility and security of supply are making conventional resources more risky, and this insecurity is complex to predict or address. For example, 2021 has proven a disruptive year for fossil fuels in the UK, with driver shortages affecting the supply of liquid fuels, and a gas supply crisis leading to the collapse of numerous energy firms and sharp rises in energy prices (by 17% in November 2021 alone, Energy Saving Trust, 2021). Therefore, the higher capital outlay and potential associated risks of clean technologies, are becoming smaller barriers. Although some industries may need a regulatory push in the direction of sustainability, clean technologies are becoming viable and sustainable, in economic terms as well as environmental terms.

The issue of higher capital costs for sustainable technology could be overcome with changes to current systems and procedures. With the example of battery electric vehicles, the rise in vehicle leasing over outright purchasing could help more widespread adoption. A straightforward monthly payment for the consumer, where the leasing company can take on the initial financial burden of the higher upfront purchase price instead of the customer, could make electric vehicles more widely accessible. The financial risks can thus be taken by larger companies rather than individuals, or even by the manufacturers who could lease their own vehicles. Rail presents a similar situation, where the ROSCOs effectively lease rolling stock to the TOCs - meaning there is an opportunity for ROSCOs, which specialise in rail rolling stock, to innovate and improve their specialism into sustainable traction technologies. For industry, the higher upfront costs of sustainable options carry less weight in comparison to the overall capital outlay for a project development. The Government could also intervene to provide economic assurances to reduce the perception of risk, and encourage the adoption of clean technology. There is not going to be one single method or driving force which works for all situations. Having cost-effective sustainable options, and the systems in place to provide these services, is vital to the success of a sustainable future. Regulatory frameworks need to support decision-making, to implement the large-scale deployment of more sustainable technologies.

8.3.2. Decision-Making for Sustainability

There are measures which can be put in place to encourage and support sustainable practices. Economic practices, such as carbon taxation, can be a form of externality internalisation. In theory, implementing carbon taxes leads to a natural reshuffling of economic markets, to account for the carbon cost and thus reduce emissions to reduce the cost (Maibach et al., 2008). Regulatory measures can have a more direct and defined impact. For the British rail system, the only regulations governing the question of sustainability on the railways were EU Directive 2004/26/EC, stages IIIA (2006) and IIIB (2012), placing emissions limits on new engines (Norris et al., 2016). No legislation could be found to mandate the replacement of trains built before those regulatory limits, or to replace the EU emissions legislation post-Brexit. The Technical Specifications for Interoperability (TSIs) define the technical and operational standards of rail in order to ensure interoperability of rail between EU countries (EU Directive 2016/797), and these have been replaced in GB by National Technical Specification Notices (NTSNs) from January 2021 (EU Agency for Railways, 2021). Although there is a NTSN specifically addressing the issue of noise; environmental degradation, and particularly the consideration of emissions, do not feature prominently within these regulations (DfT, 2020b). The only mention of emissions, in both TSIs and NTSNs is in the context of fire, and ensuring the materials selected to construct the train do not release harmful emissions when burnt (EUAR, 2021; DfT, 2020). The removal of all diesel only trains by 2040 is a guiding principle, however no penalties for non-compliance have been established yet, and a regulatory framework could be needed to achieve the removal of diesel rail in practice (Department for Transport, 2018a). In terms of legislation, this is not sufficient to push the companies involved into improving the sustainability of rail. The Rail

Industry Decarbonisation Taskforce published a report in 2019 with five strategic recommendations for rail decarbonisation. Of these, one recommendation was for clear, consistent, and enabling policies set out by Government. Overall, without government input, there is little required for companies involved in running the railways to consider around sustainability when making decisions. Without legal sustainability requirements beyond the engine emissions limits, there is no legally enforceable action to improve sustainability.

Aside from enforcing sustainable decision-making through regulation, conditions can be put in place to encourage sustainability, based on other factors. This research has shown that sustainable options can be cost-effective. However, it does not seem enough for an option to be cheaper and more sustainable, to lead to a switch in technology. Technological transition theories show that there is a fear of change. Implementing even a positive change creates disruption, whilst those involved acquire the necessary acceptance and knowledge of the new process or technology (Miller, 2017). To encourage sustainability, measures can be taken to minimise the effect of disruption. Introducing fuel cell technology on rail is a less disruptive change than introducing change in an area which requires involvement from different areas of society, such as private vehicles or home heating systems. This means there is an opportunity to trial the new fuel cell technology with minimised disruption to society. To be readily accepted, a change needs to be directly beneficial to those implementing the change and suffering the impacts of disruption. In the transition from coal to diesel rail for example, the change was visibly and physically beneficial to the workers and passengers on rail, and so the change was generally accepted (BBC Four Timeshift, 2008). Transitioning to clean technology has less demonstrable benefits to the user, which leads to lower enthusiasm to overcome the disruption. Sustainability needs to be seen as an opportunity which directly benefits the entity, rather than a 'tick-box exercise'. Sustainable can be used as a Unique Selling Point (USP), and an opportunity for growth within a more ecological ethos. At the opposite end, sustainability can be seen as a threat to a profitable business as usual. The House of Commons Environmental Audit Committee report on Greening Finance (2018) explored in detail the financial risks and opportunities of sustainability and climate change. The report detailed the risks of ignoring long-term considerations over short-term returns (especially for pension funds) and recommended the mandatory implementation of climate risk reporting for financial institutions. Although focused on finance, this mandatory reporting could support sustainability efforts in other sectors. There needs to be an external impetus, whether that is through regulation, competition, or economic measures. Responsibility needs to be accurately defined, as well as the repercussions for non-compliance. But also, sustainability needs to be a common goal, above financial profit, which becomes the target for all areas of the economy to strive for.

8.4. Limitations and Further Research

This section addresses some of the limitations of the data and analysis procedure, as well as further areas this thesis could lead into. The following paragraphs first look into the limitations of the research due to missing or unreliable data, before considering how improvements could be made and the analysis developed in further detail. Areas where this research could be taken further, or contribute to, are then outlined in the final paragraph. The value of this research has brought together emissions, monetisation, and costing data, regarding the rail industry and new technology in the form of fuel cell rail, and there is an opportunity to develop this further in decarbonisation efforts.

The limitations to the data used in the analysis of this thesis stem from unavailability. For example, the commercially sensitive nature of costing data means the data used is mostly theoretical, and could differ from costs encountered in practice. The costing data used was mostly found from conference proceedings and other comparative research-based studies. The internal cost analysis could be improved with availability of capital and operational costing data directly from the companies involved in rail. The analysis could also be developed and improved by the rail industry, which would have the detail necessary to make the analysis more accurate. Fortunately, a study containing sufficient emissions data to complete an accurate emissions analysis could be found. However, a greater collection of emissions data for British trains would enable accurate and wider evaluation of rail emissions. Monetisation of the emissions is an inherently inaccurate science, and this has been discussed in Chapter 5. An update and improved accessibility to external cost methodologies could improve external cost evaluation, and increase recognition for the negative impacts of unsustainable practices. Likewise, the carbon monetisation could be improved, with carbon costs based on the true negative impact of carbon, rather than a market value. Improving the analysis with more accurate data would strengthen and increase the accuracy of the conclusions made.

There are also limitations in the analysis procedure, due to simplifications and omissions. Although estimations have been made for the Britain-wide rail network, the detailed analysis comparing rail technologies has only been performed on the three specific case studies, and the results may not be transferrable to other routes. The emissions evaluation and impact analysis looked exclusively at the production and use of fuel, however this is not the only source of negative impact. A full Life Cycle Assessment, which assesses resource use, human health, and ecological detriment over the full lifecycle of a product or service, could be used to give a more complete evaluation of the impact of rail over different assessment criteria (International Organisation for Standardisation, 2006). This could, for example, include the impacts of emissions production and material use in the construction of infrastructure for fuel production, such as wind turbine construction, which would assign an impact and resulting external costs to the currently least-emitting option for rail traction. A full LCA might be expected to alter the analysis results, dependent on the level of importance placed on each area of impact: for example if platinum depletion is ranked as a more significant impact than fossil fuel depletion, this would benefit diesel rail. The interpretation of LCA results, and the importance ranking of impacts, would be key to determining the relative impact of rail traction technologies. The analysis in the thesis is simplified from an LCA, in assuming that the most significant area in environmental and health pollution is the emissions produced during the service lifetime, and indeed from a climate change perspective, it is the release of harmful emissions which are the largest contributory factor.

Finally, the financial analysis does not include the costs involved in a network-wide technology transition and the setup of a new system for fuel cell rail. This means the assumption has been made that costs could be compared on a level playing field. In practice, there would be additional costs of staff retraining, deposition of old rolling stock, potentially implementing a new regulatory framework and reorganisation of the system, and additional infrastructure costs for distribution networks. On the other hand, there are also benefits which have not been included, such as the elimination of diesel transport on road, and the subsequent emissions and congestion reductions. Furthermore, there may be costs involved in the running of rail which were not found in the research and so have been unintentionally omitted.

The discussions throughout this thesis have covered the topics of external costing, Lifetime Costing, technological transitions, rail system organisation, and the practical implications of a fuel cell rail system. These areas of discussion could be taken for further in-depth evaluation and development. The aim of this thesis was to bring all the different elements together into a comprehensive overview, but this inevitably leaves space for a more in depth look into the topics covered. Technological transition is its own area of research, and could be combined with further detail of the practical implications of operating a fuel cell rail system, to develop a detailed plan for the implementation of fuel cell rail in Britain. The organisation of the rail system, with inclusion of sustainability at its core, and the role of Government involvement into the railways, warrant further examination, as this is an area which could have a significant impact on the spread of sustainable development in other areas of transport and other sectors of the British economy. The idea of cost-effective sustainability is an important outcome of this research, and offers an opportunity to investigate whether this is becoming more common and whether discussions around the necessity to reduce the cost of sustainable technologies have become redundant. This research could develop further in areas which have not been discussed in detail, such as other areas of the transport system, and the importance of identifying and targeting optimal areas for the roll-out of a new technology, with minimised disruption and opposition to change. This research has shown that the idea of decarbonising does not necessarily carry a higher cost than the environmentally detrimental business as usual.

8.5. Summary

This chapter presented an appraisal of the findings of this thesis, explored the financial viability of sustainability and its inclusion into decision-making, and reviewed the limitations of this research and further development routes. The thesis explored the emissions and dimensions of cost, both internal and external, of options for rail traction in Britain. The analysis showed that the lowest emission option for rail, based on traction emissions from fuel production and use phases, is fuel cell rail with hydrogen produced from electrolysis with renewable energy sources. The analysis of internal costs on a 30-year lifetime basis showed that this lowest-emission option is also the lowest-cost option. Inclusion of the external cost analysis did not impact the internal cost analysis enough to alter the comparison of costs, but further emphasised the financial viability of the lowest-emitting option for rail. This means that in this particular case, fuel cell rail is financially viable without the need for change in the economic system to include external costs. An exploration into the financial viability of sustainable options showed that renewable energy is also at the stage where it is becoming lower-cost than fossil fuel options, and even becoming lower-cost against some coal-powered installed capacity.

Rail emissions for 2019 were 2.5 $MtCO_2e$, equivalent to 2% of UK transport emissions (DfT, 2020). In comparison to other transport modes, rail produces lower emissions, however, as the Government has planned to ban diesel rail from 2040, there is a drive to decarbonise rail (DfT, 2018a). About half of British rail outside of London runs on diesel trains, and calculation of external costs of emissions showed that rail is costing the city of Birmingham between one and six million pounds annually, approximated at 400 million pounds Britain-wide. Rail is uniquely placed to roll out the new technology of fuel cells, as the trains have the same benefits as electric trains in improved passenger comfort, shorter journey times, and greater reliability, but also without requiring the costly electrification infrastructure, which in many parts of Britain is unlikely to be installed, due to cost or terrain difficulties. The advantages of fuel cell rail provide an opportunity to implement fuel cell technology into transport on a large scale. Large-scale fuel cell rollout can, furthermore, lead to technology development and cost reductions, which can assist fuel cell implementation in other areas of transport or other sectors. Rail could be the 'low-hanging fruit' for fuel cell implementation, certainly in transport.

There is some emphasis on the role of Government in the adoption of fuel cell rail. The Government is already highly involved in British rail development, and is responsible for electrification programme planning and funding. As part of the British transport system, rail can tackle emissions reduction by implementing lower and zero-emission options for traction technologies. Rail can also encourage a modal shift away from private vehicles towards public transport, by providing better and more frequent services, reducing ticket prices, and even developing and increasing the rail network. This requires involvement and cooperation between the whole transport system, from Government, through business and organisations, and through to the passengers. Emissions reduction becomes severely limited if only one area of society is making changes.

This research recognises that decisions are not purely cost-based. The introduction of a new technology creates disruption, until it can be fully understood and accepted. However, this thesis does show that in some instances, sustainable decisions can also be cost-effective. It is hoped this shows that the pursuit of cost reduction and reducing environmental impact can be simultaneous factors in decision-making. Although the UK has introduced some limitations on fossil-based energy technologies, such as 2030 for the ban on sales of petrol and diesel only cars, 2040 for the removal of diesel only rail, and ultimately 2050 for net carbon neutrality, there is a lack of focus on systematic impacts, and changes which could prevent environmental and social impacts in the first place (UN IPCC, 2021; DfT et al., 2020; DfT 2018a). An economic system, which includes external costing into pricing, and redistributes the funds to those negatively impacted, would help to move closer towards sustainability, and ultimately benefit the planet and ourselves. This thesis shows that in certain applications, the pursuit of sustainability and emissions reduction no longer, necessarily, carries the higher cost burden with which sustainable options are often characterised.

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APPENDICES

Glossary of terms used in Appendices

EMU	Electric Multiple Unit (electric train type)
DMU	Diesel Multiple Unit (diesel train type)
DEMU	Diesel-Electric Multiple Unit (diesel train type)
DL	Diesel Locomotive (diesel train type)
MU	Multiple Unit (general train type)
Loco	Locomotive (general train type)
FC	Fuel Cell
Train Class	Categorisation of trains in the UK
train-km	km travelled by a whole train
v-km	km travelled by a single train carriage
/	Data not available
CO_2	Carbon dioxide
SO_2	Sulphur dioxide
VOCs	Volatile Organic Compounds (NM - non-methane)
CO	Carbon monoxide
PM	Particulate matter
CH_4	Methane
N_2O	Nitrous oxide
CO_2e	Carbon dioxide equivalent of other greenhouse gases
DALYs	Disability Adjusted Life Years, measurement of external costs
SMR	Steam methane reforming, method of hydrogen production
Electrolysis	Method of hydrogen production
Onsite	Hydrogen produced at the train depot
Offsite	Hydrogen produced at large scale and transported to the train depot
BEIS	Department for Business, Energy and Industrial Strategy (Reference)
DEFRA	Department for Environment, Farming and Rural Affairs (Reference)

APPENDIX 1: RAIL DATA

A1.1. Travel Distance Data

Table A1.1: Rail travel data within Birmingham City limits.

City Centre Station	City Limits Station	Track Length (km)	Trips per Day (in both directions)			Annual Distance (km/y)
			Week days	Saturdays	Sundays	
New Street	Blake Street	8.5	181	172	60	504477
New Street	Longbridge	7	339	320	199	808862
New Street	Marston Green	5	300	286	168	509915
New Street	Water Orton	5.5	193	193	110	363975
New Street	Acocks Green	3.75	32	34	20	41880
New Street	Rolfe Street	2	322	311	114	212445
New Street	Hamstead	4.75	121	117	59	193625
Moor Street	Yardley Wood	5	107	94	22	169929
Moor Street	Acocks Green	3.5	150	137	80	176650
Moor Street	The Hawthorns	3	198	173	64	191685
Annual Total Distance (km/y)						**3,173,443**

Source: Collected data.

Table A1.2: Rail travel data along the regional route.

Departure Station	Arrival Station	Trip Distance (km)	Trips per Day	Distance per Day (km)	Annual Distance (km/y)
Weekdays (261 per year - using 255 to account for reduced travel days)					
Moor Street	Worcester (FS/SH)	62	27	1674	426870
Moor Street	Great Malvern	75	5	375	95625
Moor Street	Kidderminster	34	32	1088	277440
Moor Street	Stourbridge Junction	22	27	594	151470
Moor Street	Snow Hill	0.8	12	9.6	2448
Moor Street	Stratford (via Whitlocks End)	47	20	940	239700
Moor Street	Stratford (via Solihull)	44	9	396	100980
Moor Street	Whitlocks End	14	31	434	110670
Moor Street	Dorridge	18	35	630	160650
Worcester (FS/SH)	Moor Street	62	30	1860	474300
Great Malvern	Moor Street	75	4	300	76500
Kidderminster	Moor Street	34	30	1020	260100
Stourbridge Junction	Moor Street	22	26	572	145860
Snow Hill	Moor Street	0.8	14	11.2	2856
Stratford (via Whitlocks End)	Moor Street	47	22	1034	263670
Straford (via Solihull)	Moor Street	44	9	396	100980
Whitlocks End	Moor Street	14	30	420	107100
Dorridge	Moor Street	18	35	630	160650
Saturdays (52 per year)					
Moor Street	Worcester (FS/SH)	62	26	1612	83824
Moor Street	Great Malvern	75	6	450	23400
Moor Street	Kidderminster	34	25	850	44200
Moor Street	Stourbridge Junction	22	23	506	26312
Moor Street	Snow Hill	0.8	9	7.2	374.4
Moor Street	Stratford (via Whitlocks End)	47	18	846	43992
Moor Street	Stratford (via Solihull)	44	10	440	22880
Moor Street	Whitlocks End	14	26	364	18928
Moor Street	Dorridge	18	30	540	28080
Worcester (FS/SH)	Moor Street	62	24	1488	77376

Rail travel data along the regional route continued.					
Departure Station	*Arrival Station*	*Trip Distance (km)*	*Trips per Day*	*Distance per Day (km)*	*Annual Distance (km/y)*
Great Malvern	Moor Street	75	6	450	23400
Kidderminster	Moor Street	34	29	986	51272
Stourbridge Junction	Moor Street	22	23	506	26312
Snow Hill	Moor Street	0.8	8	6.4	332.8
Stratford (via Whitlocks End)	Moor Street	47	21	987	51324
Stratford (via Solihull)	Moor Street	44	9	396	20592
Whitlocks End	Moor Street	14	24	336	17472
Dorridge	Moor Street	18	31	558	29016
Sundays (52 per year)					
Moor Street	Kidderminster	34	2	68	3536
Moor Street	Whitlocks End	14	1	14	728
Moor Street	Stratford (via Whitlocks End)	47	10	470	24440
Moor Street	Dorridge	18	10	180	9360
Moor Street	Snow Hill	0.8	23	18.4	956.8
Kidderminster	Moor Street	34	1	34	1768
Whitlocks End	Moor Street	14	1	14	728
Stratford (via Whitlocks End)	Moor Street	47	12	564	29328
Dorridge	Moor Street	18	12	216	11232
Snow Hill	Moor Street	0.8	23	18.4	956.8
Annual Total Distance (km/y)					**3,829,990**

Source: Collected data.

Table A1.3: Rail travel data along the long-distance route.

Departure Station	Arrival Station	Trip Distance (km)	Trips per Day	Distance per Day (km)	Annual Distance (km/y)
Weekdays (261 per year - using 255 to account for track closure and reduced travel days)					
New Street	Plymouth	378	11	4158	1060290
New Street	Penzance	507	3	1521	387855
New Street	Bristol	160	2	320	81600
New Street	Edinburgh	590	5	2950	752250
New Street	Glasgow	661	6	3966	1011330
New Street	Aberdeen	802	1	802	204510
New Street	Dundee	688	1	688	175440
New Street	Leeds	202	3	606	154530
Plymouth	New Street	378	11	4158	1060290
Penzance	New Street	507	3	1521	387855
Edinburgh	New Street	590	4	2360	601800
Glasgow	New Street	661	7	4627	1179885
Aberdeen	New Street	802	1	802	204510
Dundee	New Street	688	1	688	175440
Leeds	New Street	202	1	202	51510
York	New Street	250	1	250	63750
Newcastle	New Street	382	1	382	97410
Saturdays (52 per year)					
New Street	Plymouth	378	9	3402	176904
New Street	Penzance	507	3	1521	79092
New Street	Exeter	288	2	576	29952
New Street	Edinburgh	590	5	2950	153400
New Street	Glasgow	661	6	3966	206232
New Street	Aberdeen	802	1	802	41704
New Street	Dundee	688	1	688	35776
New Street	Leeds	202	2	404	21008
New Street	York	250	1	250	13000
Plymouth	New Street	378	12	4536	235872
Penzance	New Street	507	2	1014	52728
Exeter	New Street	288	1	288	14976
Edinburgh	New Street	590	4	2360	122720
Glasgow	New Street	661	6	3966	206232
Aberdeen	New Street	802	1	802	41704
Dundee	New Street	688	1	688	35776
Leeds	New Street	202	1	202	10504
York	New Street	250	1	250	13000
Newcastle	New Street	382	1	382	19864
Sundays (52 per year)					
New Street	Plymouth	378	9	3402	176904

Rail travel data along the long-distance route continued.					
Departure Station	*Arrival Station*	*Trip Distance (km)*	*Trips per Day*	*Distance per Day (km)*	*Annual Distance (km/y)*
New Street	Penzance	507	3	1521	79092
New Street	Edinburgh	590	5	2950	153400
New Street	Glasgow	661	4	2644	137488
New Street	Dundee	688	1	688	35776
New Street	Leeds	202	3	606	31512
New Street	York	250	1	250	13000
Plymouth	New Street	378	9	3402	176904
Penzance	New Street	507	2	1014	52728
Edinburgh	New Street	590	4	2360	122720
Glasgow	New Street	661	5	3305	171860
Dundee	New Street	688	1	688	35776
Leeds	New Street	202	2	404	21008
York	New Street	250	1	250	13000
Newcastle	New Street	382	1	382	19864
Annual Total Distance (km/y)					**10,401,731**

Source: Collected data.

Table A1.4: Rail travel data along the rural route.

Departure Station	Arrival Station	Trip Distance (km)	Trips per Day	Distance per Day (km)	Annual Distance (km/y)
Weekdays (261 per year - using 255 to account for track closure and reduced travel days)					
New Street	Bham International	15	7	105	26775
New Street	Aberystwyth	208	10	2080	530400
New Street	Pwllheli	270	5	1350	344250
Bham International	New Street	15	9	135	34425
Aberystwyth	New Street	208	8	1664	424320
Pwllheli	New Street	270	5	1350	344250
Saturdays (52 per year)					
New Street	Bham International	15	6	90	4680
New Street	Aberystwyth	208	10	2080	108160
New Street	Pwllheli	270	5	1350	70200
Bham International	New Street	15	9	135	7020
Aberystwyth	New Street	208	8	1664	86528
Pwllheli	New Street	270	5	1350	70200
Sundays (52 per year)					
New Street	Bham International	15	6	90	4680
New Street	Aberystwyth	208	6	1248	64896
New Street	Pwllheli	270	4	1080	56160
Bham International	New Street	15	6	90	4680
Aberystwyth	New Street	208	6	1248	64896
Pwllheli	New Street	270	4	1080	56160
Annual Total Distance (km/y)					**2,302,680**

Source: Collected data.

A1.2. Train Class Data

Table A1.5: Train class data for Birmingham City.

City Centre Station	City Limits Station	Train Class	Carriage Formation	Portion of Travel Distance
New Street	Blake Street	323 (EMU)	3 / 6	60% / 40%
New Street	Longbridge	323 (EMU)	3 / 6	60% / 40%
		170 (DMU)	2 / 3 / 4 / 5	10% each
		220/221 (DEMU)	4	40%
		253/254 (DL)	7	10%
		150 (DMU)	2	5%
		153 (DMU)	1	5%
New Street	Marston Green	390 (EMU)	9	35%
		350 (EMU)	4	45%
		220/221 (DEMU)	4	10%
		158 (DMU)	2 / 4	5% each
New Street	Water Orton	220/221 (DEMU)	4	35%
		170 (DMU)	2 / 3	15% / 50%
New Street	Acocks Green	220/221 (DEMU)	4 / 5	70% / 30%
New Street	Rolfe Street	390 (EMU)	9	10%
		350 (EMU)	4	40%
		220/221 (DEMU)	4 / 5	20% / 10%
		170 (DMU)	2	10%
		158 (DMU)	2 / 4	5% each
New Street	Hamstead	350 (EMU)	4	50%
		170 (DMU)	2 / 3 / 4 / 5	10 / 10 / 15 / 10 %
		153 (DMU)	2	5%
Moor Street	Yardley Wood	159 (DMU)	3 / 4	50% each
Moor Street	Acocks Green	159 (DMU)	3 / 4 / 5 / 6	10% each
		168 (DMU)	2 / 3 / 4 / 5 / 6	5/15/15/10/5 %
		170 (DMU)	6	15%
Moor Street	The Hawthorns	159 (DMU)	3 / 4 / 5 / 6	30 / 25 / 20 / 10 %
		168 (DMU)	3 / 5	5% each
		170 (DMU)	6	5%

Sources: Hobson et al. (2001), collected data.

Table A1.6: Train class data for regional case study.

	Class 165 DMU[1]				Class 350 EMU[1]	iLint FC[2,3]	
Carriage formation	2	3	4	5	4	2	4
Portion of distance	20%	50%	20%	10%	100%	60%	40%
Fuel consumption (kg or kWh/train-km)	0.58	0.95	1.16	1.53	6.56	0.3	0.6

Sources: [1]Hobson et al. (2001), [2]Alstom (2019), [3]Navas (2017).

Table A1.7: Train class data for long-distance case study.

	Class 221 DEMU[1]					Class 43 Loco[1]	Class 390 EMU[1]	FC Loco[2]
Carriage formation	4	5	8	9	10	2 loco + 8	9	2 loco + 8
Portion of distance	35%	40%	10%	5%	5%	5%	100%	100%
Fuel consumption (kg or kWh/train-km)	2.115	2.471	4.23	4.586	4.942	4.586	18.024	1.314

Sources: [1]Hobson et al. (2001), [2]Ruf et al. (2019).

Table A1.8: Train class data for rural case study.

	Class 158 DMU[1]		Class 323[1]		iLint FC[2,3]	
Carriage formation	2	+2 (divide)	3	+3 (divide)	2	+2 (divide)
Portion of distance	100%	50%	100%	50%	100%	50%
Fuel consumption (kg or kWh/train-km)	0.89	0.89	9.10	9.10	0.3	0.3

Sources: [1]Hobson et al. (2001), [2]Alstom (2019), [3]Navas (2017).

Appendix 2: Emission Factors

A2.1. Emission Factors by Train Class

Table A2.1: Emission factors for train classes used in analysis.

Train Class, Type, and Carriage Formation			Emission Factors (g/train-km)[1]					
			CO_2	SO_2	VOCs	CO	PM_{10}	NO_x
Class 150	DMU	3	3203	4.1	3.1	3.2	1.1	32.6
Class 153	DMU	1	1415	1.8	1.4	1.4	0.5	14.4
Class 158	DMU	2	2793	3.6	2.7	2.8	0.9	28.4
		3	3723	4.7	3.6	3.7	1.2	37.9
Class 159	DMU	3	3723	4.7	3.6	3.7	1.2	37.9
Class 165	DMU	2	1824	2.3	1.8	1.8	0.6	18.6
		3	2979	3.8	2.9	3	1	30.3
Class 221	DEMU	4	2594	3.3	2.5	8.2	0.9	26.8
Class 323	EMU	3	1833[1,2]	2.1	1.5	0.3	0.2	2.5
Class 350	EMU	4	1843[1,2]	2.1	1.5	0.3	0.2	2.5
Class 390	EMU	9	5063[1,2]	5.7	4.1	0.8	0.5	6.9

Source: [1]Hobson et al. (2001), [2]BEIS and DEFRA (2019).

[1,2]Calculated using train energy use data from Hobson et al. (2001), and grid CO_2 from BEIS and DEFRA (2019).

A2.2. Emission Factors for the UK Electricity Grid

Table A2.2: UK electricity grid emissions factors.

Emission Factors (g/kWh)	Prediction for the year 2020 from Hobson et al. (2001)			2018 data from BEIS and DEFRA (2019)
	High Scenario	Low Scenario	Average Scenario	
CO_2	387.95	370.00	379.00	280.88
SO_2	0.23	0.14	0.19	/
VOCs	0.03	0.03	0.03	/
CO	0.08	0.00	0.04	/
PM_{10}	0.01	0.00	0.005	/
NO_x	0.55	0.41	0.48	/
CH_4	/	/	/	0.66
N_2O	/	/	/	1.53

Sources: Hobson et al. (2001), BEIS and DEFRA (2019).

A2.3. Emissions Factors for Fuel Production

Table A2.3: Upstream emission factors for diesel and hydrogen fuel production.

Emission Factors (g/kg fuel)	Diesel Production[1]	Hydrogen Produced via Steam Methane Reforming		Hydrogen Produced via Electrolysis using Grid Electricity	
		Offsite[1]	Onsite	Offsite[2]	Onsite[3]
CO_2e	1312.5	15857	/	23208	/
CO_2	/	2300[2]	1345	/	13440[4]
NO_x	4.1	24	15.6	30.5	19.7
SO_x	4.3	21.6	2.1	71	6.7
PM	0.7	4.2	/	7.2	0
VOC	0.8	2.6	1.5	2.5	1.44

Sources: [1]Chernyavs'ka and Gullí (2009), [2]Navas, (2017), [3]Hobson et al. (2001), [4]BEIS and DEFRA (2019).

CO_2e includes CO_2, CH_4, and N_2O.

Onsite factors for SMR were estimated assuming a same relative difference as between the on and offsite electrolysis data.

APPENDIX 3: EXTERNAL COST DATA

A3.1. Handbook on External Costs of Transport Factors

Table A3.1: Handbook on the External Costs of Transport monetisation data for external costs.

		Air pollution external cost (€ct/train-km)		
Type of Train		Urban	Suburban	Rural
Passenger Diesel	Locomotive	240.6	112.0	90.4
	Railcar (MU)	204.5	87.8	63.9
Passenger Electric	Locomotive	116.9	28.5	8.4
	Railcar (MU)	116.9	28.5	8.4
	High-speed	/	/	14.0

Source: Korzhenevych et al. (2014).

A3.2. External Costs of Energy Factors

Table A3.2: External Costs of Energy monetisation data for external costs in EcoSenseLE.

Category	Region	Year	Indicator	Value	Unit
Health externalities (unit costs)	UK	2020	NO_X	8.244516	Euro/kg
Health externalities (unit costs)	UK	2020	SO_2	24.12156	Euro/kg
Health externalities (unit costs)	UK	2020	NMVOC	2.022928	Euro/kg
Health externalities (unit costs)	UK	2020	PM_{10}	2.662229	Euro/kg
Health externalities (unit costs)	UK	2020	$PM_{2.5}$	62.02373	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	NO_X	8.361487	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	SO_2	24.21003	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	NMVOC	2.124727	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	PM_{10}	2.665421	Euro/kg
Health externalities (unit costs - unknown sector)	UK	2020	$PM_{2.5}$	62.37561	Euro/kg
Health externalities (unit costs - SNAP 1)	UK	2020	NO_X	9.836189	Euro/kg
Health externalities (unit costs - SNAP 1)	UK	2020	SO_2	14.9835	Euro/kg

Source: Institute of Energy Economics and Rational Energy Use (2017).

A3.3. Results from the ExternE/EcoSenseLE Model

Table A3.3: EcoSenseLE external cost results for Birmingham City centre over one year.

EcoSenseLE Outputs	Diesel Rail (Upstream)	Diesel Rail (Downstream)	Electric Rail	Total
Health Impacts				
Classical air pollutants				
DALYs (mortality)	1.76	6.75	1.21	9.72
DALYs (morbidity)	0.39	1.50	0.267	2.16
DALYs (total)	2.15	8.25	1.47	11.87
Monetary value (2010€)	158327	594747	107902	860976
Other pollutants				
DALYs (total)	0	0.006	0.001	0.007
Monetary value (2010€)	0	293	25.7	319
Impacts on Crop Losses				
Monetary value (2010€)	-2067	-17044	-471	-19582
Impacts on Material Losses				
Monetary value (2010€)	1813	3843	1153	6809
Impacts on Ecosystem Quality Losses				
Monetary value (2010€)	8097	45925	5824	59846
Total external costs				
Monetary value (2010€)	166170	627764	114434	908368

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), all releases as low (urban). Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

Table A3.4: EcoSenseLE external cost results for regional case study, diesel and electric rail.

EcoSenseLE Outputs	Upstream Diesel		Downstream Diesel		Electricity	
	Annual	Lifetime	Annual	Lifetime	Annual	Lifetime
Health Impacts						
Classical air pollutants						
DALYs (mortality)	3.52	106	14.2	426	1.49	44.8
DALYs (morbidity)	0.78	23.5	3.16	94.9	0.305	9.15
DALYs (total)	4.30	130	17.4	521	1.80	53.9
Monetary value (2010€)	316653	9547908	1481785	44451842	154051	4619887
Monetary value (2020£)	305491	9211345	1429552	42884914	148621	4457036
Other pollutants						
DALYs (total)	0	0	0.009	0.257	0.002	0.050
Monetary value (2010€)	0	0	514	15421	99.1	2977
Monetary value (2020£)	0	0	496	14878	95.6	2872
Impacts on Crop Losses						
Monetary value (2010€)	-4134	-125037	-35794	-1073917	-3242	-97203
Monetary value (2020£)	-3988	-120629	-34532	-1036061	-3127	-93777
Impacts on Material Losses						
Monetary value (2010€)	3626	109295	8094	242816	1107	33194
Monetary value (2020£)	3499	105442	7809	234257	1068	32024
Impacts on Ecosystem Quality Losses						
Monetary value (2010€)	16193	488686	96627	2898752	8969	268974
Monetary value (2020£)	15622	471460	93221	2796571	8653	259492
Total external costs						
Monetary value (2010€)	332339	10020852	1551226	46534914	160985	4827829
Monetary value (2020£)	320624	9667617	1496546	44894558	155310	4657648

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), all releases as low (urban). Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

Table A3.5: EcoSenseLE external cost results for regional case study, fuel cell rail.

EcoSenseLE Outputs	Offsite SMR	Onsite SMR	Offsite Electrolysis	Onsite Electrolysis
	Lifetime	Lifetime	Lifetime	Lifetime
Health Impacts				
Classical air pollutants				
DALYs (mortality)	246	90.1	565	139
DALYs (morbidity)	54.5	19.2	115	28.3
DALYs (total)	300	109	680	167
Monetary value (2010€)	26108945	9303571	59585956	14292063
Monetary value (2020£)	32114002	8975620	73290726	13788268
Other pollutants				
DALYs (total)	0	0	0	0.154
Monetary value (2010€)	0	0	0	9211
Monetary value (2020£)	0	0	0	8886
Impacts on Crop Losses				
Monetary value (2010€)	-358207	-225435	-510957	-300541
Monetary value (2020£)	-440595	-217488	-628477	-289947
Impacts on Material Losses				
Monetary value (2010€)	242262	52002	693137	102743
Monetary value (2020£)	297982	50169	852559	99121
Impacts on Ecosystem Quality Losses				
Monetary value (2010€)	1187125	609698	2094793	831837
Monetary value (2020£)	1460164	588207	2576595	802515
Total external costs				
Monetary value (2010€)	27180125	9739837	61862929	14935312
Monetary value (2020£)	33431553	9396508	76091402	14408842

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), all releases as low (urban). Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

Table A3.6: EcoSenseLE external cost results for long-distance case study, diesel and electric rail.

EcoSenseLE Outputs	Upstream Diesel		Downstream Diesel		Electricity	
	Annual	Lifetime	Annual	Lifetime	Annual	Lifetime
Health Impacts						
Classical air pollutants						
DALYs (mortality)	25.2	757	39.8	1196	9.25	278
DALYs (morbidity)	6.04	181	11.0	330	2.26	67.8
DALYs (total)	31.3	939	50.8	1526	11.5	345
Monetary value (2010€)	2344416	70332469	4491321	134828429	1014939	30445681
Monetary value (2020£)	2261775	67853250	4333002	130075727	979162	29372470
Other pollutants						
DALYs (total)	0	0	0.096	2.86	0.012	0.370
Monetary value (2010€)	0	0	5746	171800	740	22201
Monetary value (2020£)	0	0	5543	165744	714	21419
Impacts on Crop Losses						
Monetary value (2010€)	-33222	-996653	-128000	-3843473	-24167	-724962
Monetary value (2020£)	-32051	-961521	-123488	-3707990	-23315	-699407
Impacts on Material Losses						
Monetary value (2010€)	29066	871991	28349	851078	8253	247577
Monetary value (2020£)	28042	841253	27350	821077	7962	238850
Impacts on Ecosystem Quality Losses						
Monetary value (2010€)	129914	3897421	343050	10298290	66874	2006095
Monetary value (2020£)	125335	3760037	330957	9935275	64517	1935380
Total external costs						
Monetary value (2010€)	2470174	74105229	4740466	142306124	1066639	31996593
Monetary value (2020£)	2383101	71493020	4573364	137289833	1029040	30868713

Source: Institute of Energy Economics and Rational Energy Use (2017). Scenario specification: Additional emissions, in Great Britain, future scenario (2020), 30% urban low-release, 70% rural low-release. Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years. Negative crop losses indicates fertilising effect from NO_x.

Table A3.7: EcoSenseLE external cost results for long-distance case study, fuel cell rail.

EcoSenseLE Outputs	Offsite SMR	Onsite SMR	Offsite Electrolysis	Onsite Electrolysis
	Lifetime	Lifetime	Lifetime	Lifetime
Health Impacts				
Classical air pollutants				
DALYs (mortality)	1850	608	4494	977
DALYs (morbidity)	449	161	952	239
DALYs (total)	2298	769	5445	1216
Monetary value (2010€)	203671729	67829185	481874176	107175352
Monetary value (2020£)	250516226	65438207	592705236	103397421
Other pollutants				
DALYs (total)	0	0	0	1.30
Monetary value (2010€)	0	0	0	78071
Monetary value (2020£)	0	0	0	75319
Impacts on Crop Losses				
Monetary value (2010€)	-3039657	-1912388	-4347064	-2552835
Monetary value (2020£)	-3738778	-1844976	-5346889	-2462847
Impacts on Material Losses				
Monetary value (2010€)	2063813	441183	5881836	871306
Monetary value (2020£)	2538490	425631	7234658	840593
Impacts on Ecosystem Quality Losses				
Monetary value (2010€)	10083476	5172687	17794568	7063342
Monetary value (2020£)	12402676	4990350	21887319	6814359
Total external costs				
Monetary value (2010€)	212779360	71530668	501203516	112635236
Monetary value (2020£)	261718613	69009212	616480325	108664844

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), 30% urban low-release, 70% rural low-release. Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

Table A3.8: EcoSenseLE external cost results for rural case study, diesel and electric rail.

EcoSenseLE Outputs	Upstream Diesel		Downstream Diesel		Electricity	
	Annual	Lifetime	Annual	Lifetime	Annual	Lifetime
Health Impacts						
Classical air pollutants						
DALYs (mortality)	1.70	51.1	5.96	179	1.07	32.1
DALYs (morbidity)	0.413	12.4	1.69	50.8	0.269	8.06
DALYs (total)	2.12	63.5	7.66	230	1.34	40.2
Monetary value (2010€)	159116	4772722	680450	20412903	118604	3557367
Monetary value (2020£)	153507	4604484	656464	19693349	114423	3431970
Other pollutants						
DALYs (total)	0	0	0.005	0.141	0.002	0.044
Monetary value (2010€)	0	0	283	8483	88.2	2644
Monetary value (2020£)	0	0	273	8184	85.1	2551
Impacts on Crop Losses						
Monetary value (2010€)	-2284	-68337	-19626	-588796	-2877	-86332
Monetary value (2020£)	-2203	-65928	-18934	-568041	-2775	-83289
Impacts on Material Losses						
Monetary value (2010€)	1996	59910	4454	133630	983	29483
Monetary value (2020£)	1926	57798	4297	128919	949	28444
Impacts on Ecosystem Quality Losses						
Monetary value (2010€)	8924	267447	52923	1587613	7962	238893
Monetary value (2020£)	8609	258019	51057	1531650	7681	230472
Total external costs						
Monetary value (2010€)	167752	5031742	718484	21553834	124761	3742055
Monetary value (2020£)	161839	4854373	693158	20794061	120363	3610147

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), 20% urban low-release, 80% rural low-release. Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

Table A3.9: EcoSenseLE external cost results for rural case study, fuel cell rail.

EcoSenseLE Outputs	Offsite SMR	Onsite SMR	Offsite Electrolysis	Onsite Electrolysis
	Lifetime	Lifetime	Lifetime	Lifetime
Health Impacts				
Classical air pollutants				
DALYs (mortality)	91.7	29.7	225	48.0
DALYs (morbidity)	22.6	8.14	47.9	12.1
DALYs (total)	114	37.8	273	60.1
Monetary value (2010€)	10154408	3353907	24182540	5320027
Monetary value (2020£)	12489922	3235682	29744524	5132496
Other pollutants				
DALYs (total)	0	0	0	0.066
Monetary value (2010€)	0	0	0	3952
Monetary value (2020£)	0	0	0	3812
Impacts on Crop Losses				
Monetary value (2010€)	-153405	-96835	-220048	-129240
Monetary value (2020£)	-188689	-93421	-270659	-124685
Impacts on Material Losses				
Monetary value (2010€)	104238	22339	297194	44064
Monetary value (2020£)	128213	21552	365548	42511
Impacts on Ecosystem Quality Losses				
Monetary value (2010€)	509285	261884	900105	357462
Monetary value (2020£)	626421	252653	1107129	344861
Total external costs				
Monetary value (2010€)	10614526	3541296	25159791	5596264
Monetary value (2020£)	13055867	3416465	30946542	5398996

Source: Institute of Energy Economics and Rational Energy Use (2017).
Scenario specification: Additional emissions, in Great Britain, future scenario (2020), 20% urban low-release, 80% rural low-release. Classical air pollutants are SO_2, VOCs, PM_{10}, NO_x. Other pollutants is CO. DALYs - Disability Adjusted Life Years.
Negative crop losses indicates fertilising effect from NO_x.

A3.4. CO_2 Monetisation Factors

Table A3.10: Carbon dioxide monetisation factors and increases.

Year	CO_2e Cost (£/tCO_2e)		
	Low	Central	High
2020	37.82	74.55	112.37
2021	37.82	75.63	114.53
2022	38.90	77.79	115.61
2023	38.90	78.87	117.77
2024	39.98	79.95	119.93
2025	41.06	81.03	122.09
2026	41.06	82.11	123.17
2027	42.14	83.19	125.33
2028	42.14	85.35	127.49
2029	43.22	86.43	129.65
2030	43.22	87.52	130.73
2031	47.54	95.08	142.62
2032	51.86	103.72	155.58
2033	56.18	111.29	167.47
2034	59.42	119.93	179.35
2035	63.75	127.49	192.32
2036	68.07	136.14	204.20
2037	72.39	143.70	216.09
2038	75.63	152.34	227.97
2039	79.95	159.90	240.94
2040	84.27	168.55	252.82
2041	88.60	176.11	264.71
2042	91.84	184.75	276.59
2043	96.16	192.32	289.56
2044	100.48	200.96	301.44
2045	104.80	208.52	313.33
2046	108.04	217.17	325.21
2047	112.37	224.73	338.18
2048	116.69	233.37	350.06
2049	121.01	240.94	361.95
2050	124.25	249.58	373.83

Source: DfT (2021b).

A3.5. Results from the CO_2e Costing

Table A3.11: CO_2e costs for Birmingham City centre over one year.

	CO_2e Cost (£)		
	Low	Central	High
Upstream Diesel			
For year 2020	210,443	414,874	625,317
Downstream Diesel			
For year 2020	53,129	104,741	157,870
Electricity			
For year 2020	163,508	322,345	485,853

Table A3.12: CO_2e costs for the regional case study.

	CO_2e Cost (£)		
	Low	Central	High
Upstream Diesel			
For year 2020	106,386	209,732	316,118
30-year lifetime cost 2020 - 2050	6,103,511	12,207,022	18,322,692
Downstream Diesel			
For year 2020	443,795	874,910	1,318,705
30-year lifetime cost 2020 - 2050	25,461,155	50,922,310	76,434,185
Electricity			
For year 2020	266,989	526,351	793,340
30-year lifetime cost 2020 - 2050	15,317,563	30,635,127	45,983,203
Offsite SMR			
For year 2020	333,153	656,787	989,940
30-year lifetime cost 2020 - 2050	19,113,458	38,226,916	57,378,448
Onsite SMR			
For year 2020	194,861	384,155	579,017
30-year lifetime cost 2020 - 2050	11,179,481	22,358,961	33,560,711
Offsite electrolysis			
For year 2020	1,411,723	2,783,110	4,194,833
30-year lifetime cost 2020 - 2050	80,992,547	161,985,094	243,138,980
Onsite electrolysis			
For year 2020	825,814	1,628,033	2,453,847
30-year lifetime cost 2020 - 2050	47,378,123	94,756,245	142,228,747

Table A3.13: CO_2e costs for the long-distance case study.

	CO_2e Cost (£)		
	Low	Central	High
Upstream Diesel			
For year 2020	848,509	1,672,774	2,521,283
30-year lifetime cost 2020 - 2050	48,680,157	97,360,314	146,137,444
Downstream Diesel			
For year 2020	1,505,714	2,968,407	4,474,121
30-year lifetime cost 2020 - 2050	86,384,946	172,769,892	259,326,919
Electricity			
For year 2020	1,991,297	3,925,700	5,916,997
30-year lifetime cost 2020 - 2050	114,243,564	228,487,128	342,958,268
Offsite SMR			
For year 2020	903,786	1,781,749	2,685,535
30-year lifetime cost 2020 - 2050	51,851,492	103,702,983	155,657,765
Onsite SMR			
For year 2020	529,217	1,043,314	1,572,531
30-year lifetime cost 2020 - 2050	30,361,946	60,723,892	91,146,320
Offsite electrolysis			
For year 2020	11,989,002	23,635,462	35,624,464
30-year lifetime cost 2020 - 2050	687,826,193	1,375,652,386	2,064,848,751
Onsite electrolysis			
For year 2020	7,013,194	13,826,011	20,839,204
30-year lifetime cost 2020 - 2050	402,356,946	804,713,893	1,207,872,347

Table A3.14: CO_2e costs for the rural case study.

	CO_2e Cost (£)		
	Low	Central	High
Upstream Diesel			
For year 2020	58,326	114,985	173,311
30-year lifetime cost 2020 - 2050	3,346,231	6,692,461	10,045,358
Downstream Diesel			
For year 2020	243,205	479,461	722,666
30-year lifetime cost 2020 - 2050	13,953,009	27,906,018	41,886,822
Electricity			
For year 2020	237,132	467,489	704,622
30-year lifetime cost 2020 - 2050	13,604,617	27,209,234	40,840,951
Offsite SMR			
For year 2020	200,421	395,116	595,537
30-year lifetime cost 2020 - 2050	11,498,448	22,996,896	34,518,249
Onsite SMR			
For year 2020	117,155	230,963	348,119
30-year lifetime cost 2020 - 2050	6,721,366	13,442,733	20,177,488
Offsite electrolysis			
For year 2020	606,258	1,195,194	1,801,452
30-year lifetime cost 2020 - 2050	34,781,873	69,563,747	104,414,906
Onsite electrolysis			
For year 2020	354,642	699,151	1,053,793
30-year lifetime cost 2020 - 2050	20,346,315	40,692,630	61,079,475

Appendix 4: Capital Cost Data

A4.1. Train Purchase Cost Data

Table A4.1: Costing data for rolling stock capital costs.

Item	Cost Unit	Cost	Source
Diesel rail			
Commuter DMU, average	2010£/train	1,400,000	Jan et al. (2011)
3-car regional DMU, average	2017£/train	1,500,000	Pettit (2017)
DMU average for regional and rural case studies	2020£/train	1,698,000	Calculated
Intercity DMU, average	2017£/train	4,000,000	Pettit (2017)
Intercity DMU, average	2017£/train	4,150,000	Navas (2017)
Intercity DMU average for long-distance case study	2020£/train	4,319,500	Calculated
Electric rail			
Class 380 EMU	2010£/train	1,400,000	Jan et al. (2011)
Class 379 EMU	2010£/train	1,300,000	
Class 378 EMU	2010£/train	1,000,000	
Class 350 EMU	2010£/train	1,300,000	
Class 360 EMU	2010£/train	1,100,000	
Class 377 EMU	2010£/train	1,000,000	
Class 375 EMU	2010£/train	1,000,000	
Class 357 EMU	2010£/train	1,180,000	
Class 334 EMU	2010£/train	1,180,000	
EMU average for regional and rural case studies	2020£/train	1,499,267	Calculated
Intercity EMU for long-distance case study	2020£/train	4,240,000	Assumed comparable to intercity DMU
FC rail			
Coradia iLint FC train	2017€/train	5,300,000	Navas (2017)
FC train average for regional and rural case studies	2020£/train	4,775,300	Calculated
Class 66 loco, new with FC	2005£/unit	2,000,000	Marin et al. (2010)
Mainline loco with FC (Germany)	2019€/unit	5,440,000	Ruf et al. (2019)
Mainline loco with FC (Sweden)	2019€/unit	5,200,000	
Mainline loco with FC (Estonia)	2019€/unit	3,900,000	
FC loco average for long-distance case study	2020£/unit	3,839,750	Calculated

Table A4.2: Additional information and data for rolling stock capital costs.

Item	Unit	Data	Source
Average distance travelled per DMU	km/day	560	Kent et al. (2016)
Coradia iLint FC train range	km/refuel	600-850	Bünger (2017)
Number of trains for regional case study (diesel)	train units	35	Angel Trains Limited (2019)
Number of trains used for regional electric analysis	train units	25	Estimated based on service provision
Number of trains used for regional FC analysis	train units	37	Estimated with 500km max daily range + 50% excess for extra service provision
Number of trains for long-distance case study (diesel)	train units	50	Angel Trains Limited (2019)
Number of trains used for long-distance electric analysis	train units	32	Estimated based on service provision
Number of trains used for long-distance FC analysis	train units	64	Estimated based on iLint range with 2 loco for each service
Number of trains for rural case study (diesel)	train units	20	Angel Trains Limited (2019)
Number of trains used for rural electric analysis	train units	15	Estimated based on service provision
Number of trains used for rural FC analysis	train units	15	Estimated with 570km max daily range

A4.2: Infrastructure Cost Data

Table A4.3: Costing data for infrastructure capital costs.

Item	Cost Unit	Cost	Source
Electrification project plan: London-Cardiff, 240 km (65% double, 35% four-track)	2017£	5,580,000,000	Butcher, (2017a)
Electrification project plan: Cardiff-Bridgend, 25 km (double track)	2017£	105,000,000	
Electrification project plan: Oxenholme-Windermere, 16 km (single track)	2017£	16,000,000	
Electrification project plan: Selby-Hull, 34 km (double track)	2017£	97,300,000	
Electrification project plan: Wigan-Bolton, 12 km (double track)	2017£	37,000,000	
Electrification project plan: Wales Valley Lines, 172 km (75% double, 25% single track)	2017£	738,000,000	
Track electrification cost in Europe (unspecified single/double)	2010 €/km	1,350,000	Marin et al. (2010)
Single track electrification cost	2017 £/mile	1,500,000	Pettit (2017)
Average electrification cost per single track for more local and urban routes	2020 £/km	1,626,064	Calculated based on all except London-Cardiff
Average electrification cost per single track for larger, more difficult routes	2020 £/km	3,670,274	Calculated based on London-Cardiff and Wales Valley
Average electrification cost per single track for remote and rural routes	2020 £/km	1,945,674	Calculated based on Wales Valley
Hydrogen refuelling station infrastructure cost	2016£	4,355,000	Kent et al. (2016)
Additional hydrogen refuelling point cost	2016£	400,000	

Table A4.4: Additional information and data for infrastructure capital costs.

Item	Unit	Data
Regional case study data		
Total route length (including both routes to Stratford)	km	166
Route length to electrify	km	154
Track type along route	92% double, 8% four	
Total track to electrify	km	333
Portion of route shared with other services	/	20%
Portion of share of usage on shared route	/	76%
Equivalent track to electrify if sharing cost with other services	km	312
Number of train depots for route	/	1
Number of hydrogen stations	/	1
Number of additional hydrogen refuelling points	/	1
Long-distance case study data		
Total route length	km	1,380
Route length to electrify	km	969
Track type along route	100% double	
Total track to electrify	km	1938
Portion of route shared with other services	/	100%
Portion of share of usage on shared route	/	24%
Equivalent track to electrify if sharing cost with other services	km	457
Number of train depots for route	/	4
Number of hydrogen stations	/	4
Number of additional hydrogen refuelling points	/	0
Rural case study data		
Total route length	km	
Route length to electrify	km	260
Track type along route	20% double, 80% single	
Total track to electrify	km	312
Portion of route shared with other services	/	20%
Portion of share of usage on shared route	/	17%
Equivalent track to electrify if sharing cost with other services	km	226
Number of train depots for route	/	1
Number of hydrogen stations	/	1
Number of additional hydrogen refuelling points	/	1

Source: Collected data and estimations.

A4.3. Hydrogen Production Facilities Cost Data

Table A4.5: Costing data for hydrogen production infrastructure capital costs.

Item	Cost Unit	Cost	Source
Linde Hydroprime natural gas reformer	2016£/unit	1,700,000	Kent et al. (2016)
Hydrogenics HyStat 60 electrolyser	2016£/unit	508,831	
Siemens Silyzer 200 electrolyser	2016£/unit	970,000	
PEM electrolyser	2018£/kW	750	Walker et al. (2018)
Alkaline electrolyser	2018£/kW	600	
SOE electrolyser	2018£/kW	1640	
Onshore wind project cost - 3,000 kW	2020£	2,330,000	Renewables First (2015)
Onshore wind project cost - 3,500 kW	2020£	3,130,000	
Average onshore wind cost	2020£/kW	835	Calculated
Offshore wind project cost average	2020£/kW	2,370	Catapult (2019)
Solar farm project cost - 50 kW	2020£	30,000	Sunstore (2020)
Solar farm project cost - 50 kW	2020£	180,000	
Solar farm project cost - 50 kW	2020£	7,500,000	Solar Trade Association (2020)
Average solar farm cost	2020£/kW	750	Calculated

Table A4.6: Additional information and data for hydrogen production infrastructure capital costs.

Item	Unit	Data	Source
Hydrogen production from electrolysis 15h/day, 350 days/year, 5250 h			
Linde Hydroprime natural gas reformer	kgH_2/y/unit	231,350	Kent et al. (2016)
Hydrogenics HyStat 60 electrolyser	kgH_2/y/unit	56,875	
Siemens Silyzer 200 electrolyser	kgH_2/y/unit	210,000	
PEM electrolyser	kW/kgH_2	55	Walker et al. (2018)
Alkaline electrolyser	kW/kgH_2	51	
SOE electrolyser	kW/kgH_2	39	
Solar photovoltaic load factor (2018)	%	11.3	BEIS (2021)
Onshore wind load factor (2018)	%	28.4	
Offshore wind load factor (2018)	%	40.1	

Additional information and data for hydrogen production infrastructure capital costs continued.			
Item	*Unit*	*Data*	*Source*
Regional case study data			
Annual hydrogen production	kgH_2/y	1,608,596	From iLint H_2 consumption
Linde Hydroprime natural gas reformer	No. units	7	Based on annual H_2 requirement and potential output
Hydrogenics HyStat 60 electrolyser	No. units	28	
Siemens Silyzer 200 electrolyser	No. units	8	
PEM electrolyser size	kW	16,850	
Alkaline electrolyser size	kW	15,630	
SOE electrolyser size	kW	11,950	
Electrolyser power average	kW	14,810	Calculated
Solar farm power requirement	kW	74,000	
Onshore wind farm power requirement	kW	31,500	Calculated
Offshore wind farm power requirement	kW	21,000	
Long-distance case study data			
Annual hydrogen production	kgH_2/y	13,660,940	From FC loco consumption
Linde Hydroprime natural gas reformer	No. units	59	Based on annual H_2 requirement and potential output
Hydrogenics HyStat 60 electrolyser	No. units	240	
Siemens Silyzer 200 electrolyser	No. units	65	
PEM electrolyser size	kW	143,120	
Alkaline electrolyser size	kW	132,700	
SOE electrolyser size	kW	101,480	
Electrolyser power average	kW	125,770	Calculated
Solar farm power requirement	kW	628,000	
Onshore wind farm power requirement	kW	268,000	
Offshore wind farm power requirement	kW	178,000	
Rural case study data			
Annual hydrogen production	kgH_2/y	690,804	From iLint H_2 consumption
Linde Hydroprime natural gas reformer	No. units	3	Based on annual H_2 requirement and potential output
Hydrogenics HyStat 60 electrolyser	No. units	12	
Siemens Silyzer 200 electrolyser	No. units	3	
PEM electrolyser size	kW	7,240	
Alkaline electrolyser size	kW	6,710	
SOE electrolyser size	kW	5,130	
Electrolyser power average	kW	6,360	Calculated
Solar farm power requirement	kW	31,700	
Onshore wind farm power requirement	kW	13,500	
Offshore wind farm power requirement	kW	9,020	

A4.4. Summary of Capital Costs Results

Table A4.7: Results of the capital cost analysis.

Item	Cost (2020£)
Regional case study data	
Diesel - Rolling stock purchase (35 3-car regional DMU)	59,430,000
Electric - Rolling stock purchase (25 3-car regional EMU)	37,481,667
Electric - Infrastructure for electrification alone	540,893,815
Electric - Infrastructure for electrification shared with other services	507,125,670
FC - Rolling stock purchase (37 2-car regional)	177,411,946
FC - Refuelling infrastructure	5,230,500
FC - SMR hydrogen production facility	13,002,266
FC - Electrolysis hydrogen production facility	13,123,134
FC - Onshore wind production facility	26,317,500
FC - Offshore wind production facility	49,770,000
FC - Solar farm production facility	55,500,000
Long-distance case study data	
Diesel - Rolling stock purchase (50 5-car intercity DMU)	215,975,000
Electric - Rolling stock purchase (32 9-car intercity EMU)	135,680,000
Electric - Infrastructure for electrification alone	7,112,990,469
Electric - Infrastructure for electrification shared with other services	1,677,721,291
FC - Rolling stock purchase (64 locomotives)	245,744,000
FC - Refuelling infrastructure	19,162,000
FC - SMR hydrogen production facility	110,421,257
FC - Electrolysis hydrogen production facility	111,447,727
FC - Onshore wind production facility	223,907,619
FC - Offshore wind production facility	421,860,000
FC - Solar farm production facility	471,000,000
Rural case study data	
Diesel - Rolling stock purchase (20 3-car regional DMU)	33,960,000
Electric - Rolling stock purchase (15 3-car regional EMU)	22,489,000
Electric - Infrastructure for electrification alone	607,050,362
Electric - Infrastructure for electrification shared with other services	439,099,762
FC - Rolling stock purchase (15 2-car regional)	71,629,500
FC - Refuelling infrastructure	5,230,500
FC - SMR hydrogen production facility	5,583,763
FC - Electrolysis hydrogen production facility	5,635,669
FC - Onshore wind production facility	11,278,929
FC - Offshore wind production facility	21,377,400
FC - Solar farm production facility	23,775,000

Appendix 5: Operational Cost Data

A5.1. Fuel Cost Data

Table A5.1: Costing data for fuel operational costs.

Item	Cost Unit	Cost	Source
Consumer average diesel price	2020£/L	1.3148	BEIS (2020a)
Estimated industrial diesel price	2020£/kg	1.233	Using electric ratio
Industrial average electricity price	2020£/kWh	0.129	BEIS (2020b)
Consumer average electricity price	2020£/kWh	0.166	BEIS (2020c)
Hydrogen SMR LH2 truck delivery price	2017€/kg	7 - 9	Bünger (2017)
Hydrogen by-product CGH2 truck or train delivery price	2017€/kg	4 - 6	
Hydrogen by CGH2 pipeline supply price	2017€/kg	6 - 8	
Hydrogen reported California price	2016$/kg	12.85 - 16	California Fuel Cell Partnership (2016)
Hydrogen predicted future California price	2020$/kg	8 - 10	
Hydrogen at pump target Europe price	2020€/kg	8 to 12	Hydrogen Europe (2020)
Hydrogen produced from renewables in Germany	2018$/kg	3.23	Timperley, J. (2019)
Average imported hydrogen price	2020£/kg	7.08	Calculated

Table A5.2: Additional information and data for fuel operational costs.

Item	Unit	Data
Ratio industrial to consumer pricing for electricity	/	0.78
Regional case study data		
Diesel consumption from DMU consumption data	kg/y	3,738,070
Electricity consumption from EMU consumption data	kWh/y	25,136,541
Hydrogen consumption from iLint consumption data, with 40% of trains running as double for extra capacity	kg/y	1,608,596
Long-distance case study data		
Diesel consumption from DEMU consumption data	kg/y	29,813,961
Electricity consumption from EMU consumption data	kWh/y	187,476,817
Hydrogen consumption from FC loco consumption data	kg/y	13,660,940
Rural case study data		
Diesel consumption from DMU consumption data	kg/y	2,049,385
Electricity consumption from EMU consumption data	kWh/y	22,325,549
Hydrogen consumption from iLint consumption data	kg/y	690,804

Source: Calculated data.

A5.2: Track Cost Data

Table A5.3: Costing data for track charges operational costs.

Item	Cost Unit	Cost	Source
Class 172 variable usage charge rate	£p/v-m*	6.81	Network Rail (2020b) Cost is per train vehicle (carriage) travelled
Class 221 variable usage charge rate	£p/v-m	25.43	
Class 43 variable usage charge rate (data for whole train)	£p/train-m	202.62	
Class 158 variable usage charge rate	£p/v-m	9.33	
Class 350 variable usage charge rate	£p/v-m	12.22	
Class 390 variable usage charge rate	£p/v-m	18.96	
Class 334 variable usage charge rate	£p/v-m	11.42	
Class 175 variable usage charge rate (electric 2-carriage Coradia)	£p/v-m	18.8	

*vehicle-miles

Table A5.4: Additional information and data for track charges operational costs.

Item	Unit	Data
Regional route train-km travelled	train-km/y	3,829,990
Regional route vehicle-km travelled - diesel	v-km*/y	12,255,968
Regional route vehicle-km travelled - electric	v-km/y	15,319,960
Regional route vehicle-km travelled - FC	v-km/y	11,489,970
Long-distance route train-km travelled	train-km/y	10,401,731
Long-distance route train-km travelled - diesel Class 43	train-km/y	520,087
Long-distance route vehicle-km travelled - diesel Class 221	v-km/y	53,568,915
Long-distance route vehicle-km travelled - electric	v-km/y	93,615,579
Long-distance route train-km travelled - FC	train-km/y	10,401,731
Rural route train-km travelled	train-km/y	2,302,680
Rural route vehicle-km travelled - diesel	v-km/y	4,605,360
Rural route vehicle-km travelled - electric	v-km/y	6,908,040
Rural route vehicle-km travelled - FC	v-km/y	4,605,360

*vehicle-km

A5.3: Maintenance Cost Data

Table A5.5: Costing data for maintenance operational costs.

Item	Cost Unit	Cost	Source
Diesel Rail			
DMU average maintenance cost	2012£/train-km	4.35	Zschoche et al. (2012)
Intercity DMU average maintenance cost	2012£/train-km	3.16	
DMU average maintenance cost	2017€/train-km	0.79	Navas (2017)
Average maintenance cost for DMU	2020£/train-km	2.95	Calculated
Average maintenance cost for intercity DMU	2020£/train-km	2.22	
DMU complete overhaul cost	2017£/train	half capital value	Pettit (2017)
Diesel refuelling station maintenance cost	2017€/y	10,350	Navas (2017)
Electric Rail			
EMU average maintenance cost	2012£/train-km	2.26	Zschoche et al. (2012)
Intercity EMU average maintenance cost	2012£/train-km	2.42	
EMU average maintenance cost	2017€/train-km	0.474	Navas (2017)
Average maintenance cost for EMU	2020£/train-km	1.65	Calculated
EMU complete overhaul cost	£	25% capital value	Estimated
Passenger electrification usage charge	£p/v-m	1.9	Network Rail (2020b)
FC Rail			
FC average maintenance cost	2019€/train-km	0.9275	Ruf et al. (2019)
FC loco average maintenance cost	2019€/train-km	1.203	
Regional FC average maintenance cost	2017€/train-km	0.79	Navas (2017)
Average maintenance cost for FC	2020£/train-km	0.75	Calculated
Average maintenance cost for FC loco	2020£/train-km	0.867	
Regional FC complete overhaul cost	2017£/train	19,100	Pettit (2017)
Hydrogen refuelling station maintenance cost	2017€/y	180,000	Navas (2017)

Table A5.6: Additional information and data for maintenance operational costs.

Item	Unit	Data	Source
DMU complete overhaul needed every	hours	20,000	Kent et al. (2016)
	years	10	Pettit (2017)
	years	7.5	Porterbrook (2014)
	miles	450,000	
FC complete overhaul needed every	hours	20,000	Kent et al. (2016)
	years	5	Pettit (2017)
Regional case study data			
Regional route train-km travelled		3,829,990	train-km/y
Regional route vehicle-km travelled (electric)		15,319,960	v-km/y
Estimated number of overhauls over DMU lifetime		3	
Assumed number of diesel refuelling stations		2	
Estimated number of overhauls over EMU lifetime		1	
Estimated number of overhauls over FC lifetime		3	
Assumed number of hydrogen refuelling stations		2	
Long-distance case study data			
Long-distance route train-km travelled		10,401,731	train-km/y
Long-distance route vehicle-km travelled (electric)		93,615,579	v-km/y
Estimated number of overhauls over DMU lifetime		3	
Assumed number of diesel refuelling stations		4	
Estimated number of overhauls over EMU lifetime		1	
Estimated number of overhauls over FC lifetime		4	
Assumed number of hydrogen refuelling stations		4	
Rural case study data			
Rural route train-km travelled		2,302,680	train-km/y
Rural route vehicle-km travelled (electric)		6,908,040	v-km/y
Estimated number of overhauls over DMU lifetime		3	
Assumed number of diesel refuelling stations		2	
Estimated number of overhauls over EMU lifetime		1	
Estimated number of overhauls over FC lifetime		3	
Assumed number of hydrogen refuelling stations		2	

A5.4: Hydrogen Production Facilities Operation Cost Data

Table A5.7: Costing data for hydrogen production operational costs.

Item	Cost Unit	Cost	Source
Industrial average natural gas price	2020£/kWh	0.02484	BEIS (2020b)
Industrial average electricity price	2020£/kWh	0.129	
Offshore wind farm operational cost	2020£/kW/y	76	Catapult (2019)
Onshore wind farm operational cost	2020£/kW/y	38	Assumed half offshore
Solar farm operational cost	2020£/kW/y	13.5	Solar Trade Association (2020)

Table A5.8: Additional information and data for hydrogen production operational costs.

Item	Unit	Data	Source
Regional case study data			
Annual hydrogen consumption	kgH_2/y	1,608,596	Calculated
Linde Hydroprime SMR gas input	kWh/unit	1726	Kent et al. (2016)
	kWh/y	100,808,582	Calculated
PEM electrolyser electrical input	kW/kgH_2	55	Walker et al. (2018)
	kWh/y	88,472,769	Calculated
Alkaline electrolyser electrical input	kW/kgH_2	51	Walker et al. (2018)
	kWh/y	82,038,386	Calculated
SOE electrolyser electrical input	kW/kgH_2	39	Walker et al. (2018)
	kWh/y	62,735,236	Calculated
Electrolyser power average	kW	14,810	Calculated
Solar farm power	kW	74,000	
Onshore wind farm power	kW	31,500	
Offshore wind farm power	kW	21,000	
Long-distance case study data			
Annual hydrogen consumption	kgH_2/y	13,660,940	Calculated
Linde Hydroprime SMR gas input	kWh/unit	1726	Kent et al. (2016)
	kWh/y	856,113,132	Calculated
PEM electrolyser electrical input	kW/kgH_2	55	Walker et al. (2018)
	kWh/y	751,351,703	Calculated
Alkaline electrolyser electrical input	kW/kgH_2	51	Walker et al. (2018)
	kWh/y	696,707,942	Calculated
SOE electrolyser electrical input	kW/kgH_2	39	Walker et al. (2018)
	kWh/y	532,776,662	Calculated
Electrolyser power average	kW	125,770	Calculated
Solar farm power	kW	628,000	
Onshore wind farm power	kW	268,000	
Offshore wind farm power	kW	178,000	
Regional case study data			
Annual hydrogen consumption	kgH_2/y	690,804	Calculated
Linde Hydroprime SMR gas input	kWh/unit	1726	Kent et al. (2016)
	kWh/y	43,291,777	Calculated
PEM electrolyser electrical input	kW/kgH_2	55	Walker et al. (2018)
	kWh/y	37,994,220	Calculated
Alkaline electrolyser electrical input	kW/kgH_2	51	Walker et al. (2018)
	kWh/y	35,231,004	Calculated
SOE electrolyser electrical input	kW/kgH_2	39	Walker et al. (2018)
	kWh/y	26,941,356	Calculated
Electrolyser power average	kW	6,360	Calculated
Solar farm power	kW	31,700	
Onshore wind farm power	kW	13,500	
Offshore wind farm power	kW	9,020	

A5.5 Summary of Operational Costs Results

Table A5.9: Results of the operational cost analysis.

Item	Annual Cost (2020£)	Lifetime Cost (2020£)
Regional case study data		
Diesel - Fuel	4,607,639	138,229,165
Diesel - Track access charges	518,727	15,561,804
Diesel - Rolling stock maintenance + overhauls	11,282,748	422,839,971
Diesel - Refuelling infrastructure maintenance	18,651	559,521
Electric - Electricity	3,242,614	97,278,414
Electric - Track access charges	1,163,517	34,905,515
Electric - Rolling stock maintenance + overhauls	5,969,181	188,445,850
Electric - Electrification infrastructure maintenance	180,907	5,427,208
FC - Hydrogen fuel	11,394,658	341,839,737
FC - SMR hydrogen production	2,504,085	75,122,555
FC - Electrolysis hydrogen production	6,519,237	195,577,099
FC - Onshore wind production with electrolysis	1,197,000	35,700,000
FC - Offshore wind production with electrolysis	1,596,000	47,700,000
FC - Solar farm production with electrolysis	999,000	29,970,000
FC - Track access charges	1,342,520	40,275,594
FC - Rolling stock maintenance + overhauls	2,872,808	88,539,439
FC - Refuelling infrastructure maintenance	324,360	9,730,800
Long-distance case study data		
Diesel - Fuel	36,749,434	1,102,483,028
Diesel - Track access charges	9,121,274	273,638,231
Diesel - Rolling stock maintenance + overhauls	23,047,635	995,757,473
Diesel - Refuelling infrastructure maintenance	37,301	1,119,042
Electric - Electricity	24,184,509	725,535,283
Electric - Track access charges	11,031,395	330,941,836
Electric - Rolling stock maintenance + overhauls	17,199,647	549,909,412
Electric - Electrification infrastructure maintenance	1,105,467	33,164,003
FC - Hydrogen fuel	96,768,709	2,903,061,258
FC - SMR hydrogen production	21,265,850	637,975,506
FC - Electrolysis hydrogen production	55,364,375	1,660,931,243
FC - Onshore wind production with electrolysis	10,184,000	305,400,000
FC - Offshore wind production with electrolysis	13,528,000	405,000,000
FC - Solar farm production with electrolysis	8,478,000	254,100,000
FC - Track access charges	13,098,811	392,964,338
FC - Rolling stock maintenance + overhauls	9,020,069	281,911,640
FC - Refuelling infrastructure maintenance	648,720	19,461,600

Results of the operational cost analysis continued.		
Item	*Annual Cost (2020£)*	*Lifetime Cost (2020£)*
Rural case study data		
Diesel - Fuel	2,526,123	75,783,703
Diesel - Track access charges	267,048	8,011,437
Diesel - Rolling stock maintenance + overhauls	6,824,453	253,628,852
Diesel - Refuelling infrastructure maintenance	18,650	559,521
Electric - Electricity	2,879,996	86,399,874
Electric - Track access charges	490,303	14,709,102
Electric - Rolling stock maintenance + overhauls	5,373,389	166,823,919
Electric - Electrification infrastructure maintenance	81,574	2,447,224
FC - Hydrogen fuel	4,893,383	146,801,488
FC - SMR hydrogen production	1,075,368	32,261,033
FC - Electrolysis hydrogen production	2,799,656	83,989,677
FC - Onshore wind production with electrolysis	513,000	15,390,000
FC - Offshore wind production with electrolysis	685,000	20,550,000
FC - Solar farm production with electrolysis	427,950	12,810,000
FC - Track access charges	895,013	26,850,396
FC - Rolling stock maintenance + overhauls	1,727,200	52,766,897
FC - Refuelling infrastructure maintenance	324,360	9,730,800