Programme Area: Energy Storage and Distribution

Project: Impact Analysis

Title: Future Networks: Impact Analysis Hydrogen Final Report

Abstract:

This deliverable provides the final report for the hydrogen case studies that have been assessed as part of the project. Please refer to the Executive Summary on Page 11 for an overview of the report content.

Context:

This project assessed the potential impact of selected, identified innovations on specific types of network (relating to heat, gas, electricity and hydrogen). Generic modelled networks will be developed utilising the 2050 Energy Infrastructure Cost Calculator model developed by a separate ETI project to understand the expected costs of certain types of network. The modelled networks will provide 'business as usual data' and a useful basis for further understanding of the impact of identified innovations in terms of overall cost and network performance.

BUROHAPPOLD ENGINEERING

Energy Infrastructure Outlook 2050

Innovation Impact Analysis - Hydrogen - Final Report

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author	**Pablo Romero;Henrietta Cooke**
date	**05/01/16**
approved	**Alasdair Young**
signature	
date	**05/01/16**

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Contents

Table of Tables

Table of Figures

Glossary

Term	Definition
Abandonment	A term used in the context of the ICC to refer to the end of life of an asset and the costs associated with its removal / decommissioning. Abandonment costs are included in Lifecycle costs.
Assembly	A term used in the context of the ICC. These are collections of Components compiled using quantity multipliers to produce composite costs for these Assemblies.
Calorific Value (CV)	The CV refers to the amount of energy released when a known volume of gas is completely combusted under specified conditions
Cascade mode	Pressurization based on multiple stages of compression (i.e. from 80 to 350bars and then to 900bars)
Component	A term used in the context of the ICC. This is lowest level to which capital costs are disaggregated.
Embrittlement	This the process by which various metals, most importantly high-strength steel, become brittle and fracture following exposure to hydrogen
First costs	In this study, the term first costs refers to the initial capital cost incurred on installation of new equipment or decommissioning of existing commitment. First costs are the indexed costs at the date of installation / decommissioning and are not discounted.
Lifecycle	A term used in the context of the ICC to refer to the cost profile of an asset over its life including new build, minor and major refurbishment and ultimate abandonment / decommissioning.
Losses	As energy is transported from the point of generation through to the point of use, some of it will get lost from the system through leakage or other factors. These losses have various causes and have a cost associated with them, based on the energy price. The cost of these losses is not included in the ICC.
Net Present Value	This is the combined value of all future cash flows associated with a project discounted back to 2015. Net Present Value is the term used in the ICC however it should be noted that, as all cash flows in the cost tool are in fact costs (i.e. no 'values' or revenues are included), strictly the term should be Net Present Cost.
Normalised cost	The total cost of undertaking a project divided by a single parameter such as network length to give a cost per km or population to give a cost per capita.
Project	A term used in the context of the ICC. Projects are collections of Assemblies with specific quantity multipliers combined to produce whole Project cost estimates.
Refurbishment	A term used in the context of the ICC to refer to the minor and major overhaul of an asset during its life
Repurposing	Modifying the system to enable it to carry a different substance from the one for which it was originally designed (e.g. modifying a natural gas pipeline to carry hydrogen).
Special crossings	When pipelines cross elements such as rivers, railways or roads.
Substation	Equipment that allows heat transfer from a district heating network to an individual building's heat system.

Acronyms

Term	Definition
BCIS	Building Cost Information Services
BoQ	Bill of Quantities
Capex	Capital Expenditure
CO2	Carbon Dioxide
DNO	Distribution Network Operator
GIS	Geographical Information System
H_2	Hydrogen
HGV	Heavy Goods Vehicle
HP	High Pressure
ICC	Infrastructure Cost Calculator
IP	Intermediate Pressure
LP	Low Pressure
LTS	Local Transmission System
MEAV	Modern Equivalent Asset Value
MP	Medium Pressure
MSOA	Middle layer super output area
NG	Natural Gas
Nm^3	Normal cubic metre
NPV	Net Present Value
NTS	National Transmission System
Opex	Operational Expenditure
PM	Project Management
PRS	Pressure Reduction Station
Repex	Replacement Expenditure

1 Executive Summary

1.1 Project overview

This study brings together two strands of work within the ETI focused on understanding the cost and performance of energy infrastructure in the UK. On the one hand, the research projects undertaken by various teams looking at specific scenarios and innovations, and on the other, the Infrastructure Cost Calculator (ICC – formerly referred to as the Energy Infrastructure Outlook 2050 Cost Tool), an analysis tool based on an extensive database of energy infrastructure costs.

The research questions addressed can be divided into two broad categories:

- Firstly, questions around the configuration and cost of representative (or 'generic') networks applicable to particular situations.
- Secondly, questions around the potential impact of selected, identified innovations on specific types of network.

This report considers the research questions posed in relation to hydrogen. Separate reports are available for electricity, natural gas and heat.

The work undertaken here made use of the first version of the ICC and as such also acted as a testing phase. Some issues arose in relation to the output of the tool particularly in respect of the treatment of operational and lifecycle costs. These findings are being fed into a parallel project to develop a second version.

1.2 Key findings

Some findings are the same across all projects. These include:

- First costs are higher at later installation dates. This is due to the impact of the real-term cost trends in the ICC applied to labour, material and plant costs. There are clearly alternative views on cost trajectories and these will influence the relative impact of deferring installation.
- NPV[1] (Capex plus Opex) is lower for projects installed at a later date. Two factors come into play here: one, as expected, is the impact of discounting; the other is the way in which lifecycle costs are modelled in the ICC and the fact that the analysis has been undertaken for a fixed period of 60 years (2015 to 2075) irrespective of the installation date. Lifecycle costs include for a major refurbishment (100% of new build costs) at a fixed period after first instalment. For later installation dates, this major refurbishment may be beyond the analysis period and therefore not included in the NPV calculation.
- Opex costs represent a relatively small proportion of whole life costs. It should be noted that the modelling of opex is to be revised in the next version of the ICC which may influence the outturn values (see Section 3.2.4). Note also that opex does not include the cost of any energy lost from the system.

A summary of findings specific to each project is given in Table 1-1.

[1] In this study, the term Net Present Value (NPV) refers to the combined cash flows of a project over the project period discounted back to 2015. Note that as all cash flows in this analysis are costs (ie no revenues are included), strictly the term should be Net Present Cost. NPV is used to be consistent with the terminology used in the ICC.

Table 1-1 Key findings for hydrogen network research projects

Ref	Research task	Key findings
GENERIC NETWORKS		
H2-G-21	Representative hydrogen transmission model: transmission pipeline of different lengths required to transport hydrogen from production facilities to a) power generation sites and b) vehicle refuelling sites	• Pipe lengths (NTS 32") modelled for connection to power generation sites were 5km and 10km without the need for a compression station; pipe lengths (LTS 16") for connection to refuelling sites were modelled at longer distances up to 200km, with a compression station required for anything over 100km. • NPV/km for connecting to power stations was £5.4m for installation in 2025. • NPV/km for connections to refuelling sites was in the range £3.0m to £3.5m depending on network length with the higher cost relating to the need to add in a compression station to maintain a pressure of 30 bar. • The additional cost of the power station scenario was due to the need for larger diameter and hence more expensive pipes.
H2-G-22	Representative hydrogen distribution model: distribution pipelines (LP/MP) required to connect production facilities to vehicle refuelling stations at different capacities and contexts	• Context is a strong influencer of costs, with first costs per km increasing from rural through to urban and London. This is due to the higher costs of installing pipework in more congested areas. • Pipe costs dominate the overall network cost, particularly for the longer network lengths. • There is a small increase in cost per km for the higher capacity scenarios
INNOVATIONS		
H2-I-23	Hydrogen transmission and the impact of including storage: NTS/LTS hydrogen pipeline with a) a single salt cavern storage site and b) multiple salt cavern storage sites	• Connecting a single large storage site into the network is considerably less expensive than connecting multiple storage sites with the same total capacity (460-480m m^3) • As the pipe lengths modelled were relatively short (5-10km) the storage costs dominated the overall project cost (over 95%) • Costs per mcm are considerably higher for the multi-storage option at around £6m/mcm compared with £3.3m for the single storage option • As the counterfactual chosen has no storage its value as a comparator with the storage options is limited. The main benefit of the storage options is the storage itself and not the first cost savings associated with it. There may be other cost savings related to the better performance and greater flexibility of the H_2 power generation plant versus costs of alternative storage facilities.
H2-I-24	Hydrogen transmission network and the impact of pipeline material change: comparison of stainless steel 316L pipe with conventional steel using same pipe diameter (32" NTS)	• First costs per km are higher for the stainless steel innovation at around £5.7m/km compared with £3.9m/km for the counterfactual (2025 costs) • There is a slight reduction in cost/km for the longer stainless steel pipe lengths (2-3% lower at 10km compared with 5km) but no reduction in cost/km for the counterfactual. This requires further examination,
H2-I-25	Hydrogen distribution network and purification system	• No cost analysis was undertaken on this task as cost information on purification systems was not available from the market.

1.3 Further work

Further work could be undertaken in relation to the specifics of the tasks as follows:

- Issues over risk / safety associated with transmission pipelines at different pressures was noted as an area of interest. Further more detailed work could be undertaken on this in support of the original technical scope for the ICC.
- The original costing for the hydrogen infrastructure in the ICC was undertaken in 2012/13 in relation to equivalent natural gas infrastructure (i.e. an uplift was applied as appropriate). Studies have been undertaken since then which could be used to update the hydrogen costs in a future version of the tool.
- Further investigation required over the impact of scale rate modifiers within the ICC and how they impact on different network lengths (eg H-G-21).
- The hydrogen purification task can be revisited as products mature and cost data becomes available.

In addition, all tasks could be re-run in the second version of the ICC. This version will use a revised approach to modelling Opex and lifecycle costs which should address the issue encountered in this study in relation to the use of a fixed analysis period. ICC v2 will also incorporate different costs trends which will also impact on results.

2 Introduction

2.1 Overview

The ETI and its Members are interested in the cost effective deployment of energy infrastructure in the UK. By 2050 the UK will need to be meeting stringent targets requiring an 80% reduction in CO_2 emissions, whilst maintaining a sufficient supply of energy. In order to appropriately assess the opportunities for meeting these targets, it is necessary to understand, amongst other things, the costs and performance of the energy infrastructure that will carry energy from where it is generated to where it is consumed.

The study brings together two strands of work within the ETI aimed at addressing these issues. On the one hand, the research projects undertaken by various teams looking at specific variations and innovations, and on the other, the Infrastructure Cost Calculator (ICC – formerly referred to as the Energy Infrastructure Outlook 2050 Cost Tool), an analysis tool based on an extensive database of energy infrastructure costs. The tool is being used to enable the research teams to answer specific research questions.

The research questions addressed in this study can be divided into two broad categories:

- Firstly, questions around the configuration and cost of representative (or 'generic') networks applicable to particular situations. These network models are required to understand the expected costs, etc of certain types of typical network, the intention being to enable expedited assessment of certain types of network (at a high level) in future as the need arises, e.g. through making adjustments to the models provided as part of this work.
- Secondly, questions around the potential impact of selected, identified innovations on specific types of network. For example, questions around the difference in cost and performance between repurposing natural gas pipelines to carry hydrogen and building hydrogen pipelines from scratch. The generic networks provide the counterfactual against which the innovations can be compared.

This report considers the research questions posed in relation to hydrogen. Separate reports are available for electricity, natural gas and heat.

The study was undertaken by BuroHappold with the Sweett Group and a team of external specialists to validate the technical scoping (see Appendix A).

2.2 Approach and methodology

An overarching methodology was developed applicable to all research questions. As illustrated in Figure 2-1, key steps were to:

1. Agree the outline scope of each of the research questions with ETI.
2. Develop a detailed scope for each of the research questions including a clearly defined network design and associated Bill of Quantities (BoQ).

An important aspect of this step was to ensure that, as far as possible, the network designs were representative of the particular situation being modelled. To support this, a team of experts was engaged to provide a robust approach to validation and to ensure that assumptions and simplifications made were reasonable. The detailed scoping methodologies are particular to each research question and are covered in the relevant chapter of this report. Full copies of all Detailed Scoping reports are available separately from the ETI.

3. Cost the network design using the ICC, including costing any additional infrastructure elements not already available. For this step, the details of the Bill of Quantities generated during the detailed scoping phase were input to the tool under various contexts, capacities and timescales, thereby generating a number of data points on which to perform the analysis.

4. Analyse the cost data generated by the ICC in the context of the research question and, where relevant, compare the cost of the innovation with that of the generic counterfactual.

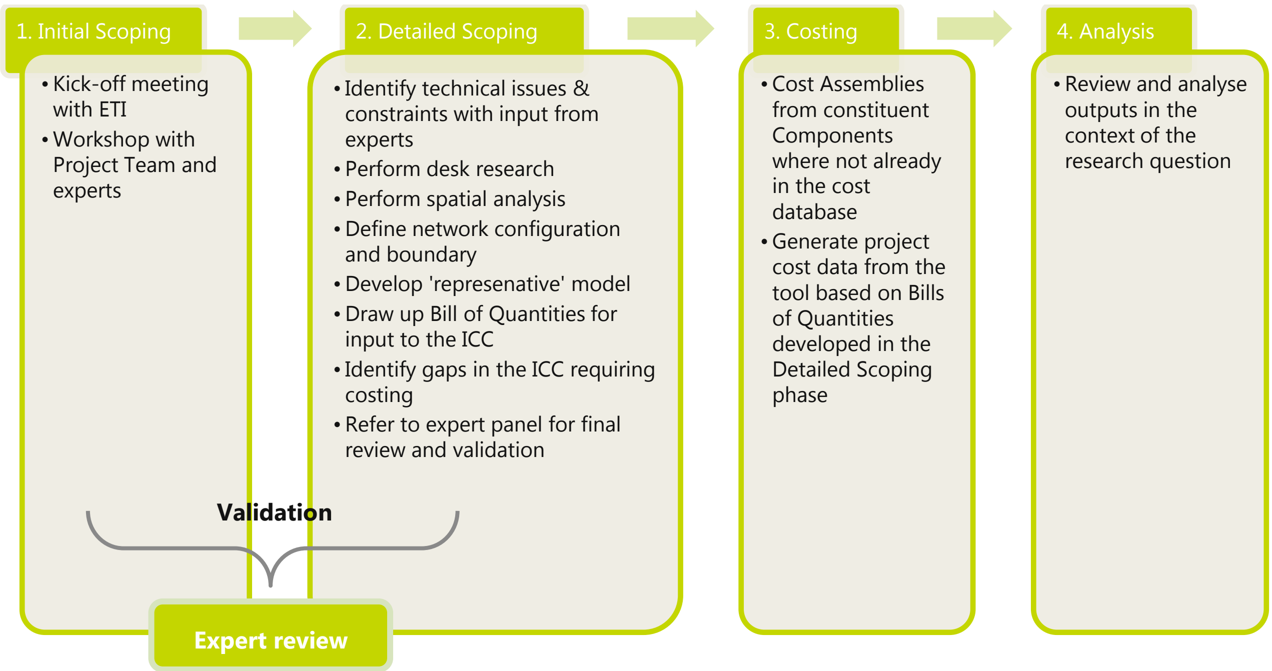


Figure 2-1 Outline methodology applied to all research questions

The ICC that underpins this analysis is a tool that was commissioned by ETI in 2012 and created by Buro Happold and the Sweett Group. It contains a wealth of information on the capital and operational costs of infrastructure related to the four energy vectors, electricity, gas, heat and hydrogen. To provide context for readers of this report, further background information on the structure and functionality of the tool is provided in Chapter 3.

2.3 Scope

A summary of the hydrogen research questions covered in this study is provided in Table 2-1. As noted above, these questions arose from within ETI's operational and strategic teams, and as such are specific to particular areas of work on which they are engaged. The table outlines the context of each research project and the value this analysis provides.

Table 2-1 Summary of hydrogen research questions covered in this study

Ref	Title	Description	Context / value added
GENERIC NETWORKS			
H2-G-21	Representative hydrogen transmission model	Transmission networks associated with connecting to power generation and transport refuelling sites	Rural context. Derivation of costs per km for transport of hydrogen in different scenarios
H2-G-22	Representative hydrogen distribution model	Distribution networks associated with connecting vehicle refuelling sites into the network	Rural, semi-urban, urban and London. Derivation of connection costs in different contexts and over different distances
INNOVATIONS			
H2-I-23	Hydrogen transmission and the impact of including storage	NTS/LTS network with two alternative storage scenarios, one with a single large storage site and one with several smaller ones. Compared with a counterfactual with no storage.	Rural context. Understanding relative impact of costs of small and large scale storage solutions.
H2-I-24	Hydrogen transmission network and the impact of pipeline material change	Comparison of costs of stainless steel 316L 32" pipelines with a standards steel counterfactual	Rural context. Understanding impact of using new materials for pipeline construction
H2-I-25	Hydrogen distribution network and purification system	Transport of hydrogen from production sites to transport refuelling sites through the distribution network incorporating a purification system suitable for refuelling vehicles	*Analysis not undertaken due to poor availability of cost data.*

2.4 Report structure

This report synthesises the work undertaken on each of the research questions and presents and discusses the findings. A chapter is included for each question using the project reference provided in Table 2-1. The analysis is based on the detailed scoping exercise that was undertaken for each project. The Detailed Scoping reports are available separately from ETI.

An overview of the ICC is provided in Chapter 3 to provide context to the reader when interpreting the results.

3 Infrastructure Cost Calculator

3.1 Introduction

This chapter explains the workings of the ICC in the context of this study. Full details of its structure and operation can be found in the ETI Energy Infrastructure 2050 Final Report, 22 November 2013, available from the ETI.

This chapter should be considered as a reference chapter to provide background to the interpretation of the data.

3.2 Cost Tool overview

The ICC is a structured database containing cost data for a broad spectrum of infrastructure elements for electricity, gas, heat and hydrogen in respect of transmission, distribution, conversion, connection and storage. It was developed over a two year period by Buro Happold in close association with the Sweett Group, combining expertise in technical design and cost modelling. The tool is under development with a second version due to be released towards the end of 2015. The analysis presented in this report was undertaken using the first version, completed in November 2013.

The following sections highlight some of the key features of the tool that are of relevance to this study.

3.2.1 Tool structure

The tool uses a modular approach to build up costs, from Component to Assembly to Project as shown in Figure 3-1.

- **Components** represent the lowest level to which capital costs are disaggregated. For example, civil engineering cost Components may include excavation, filling, surface re-instatement, etc.

- **Assemblies** are collections of Components compiled using quantity multipliers to produce composite costs for these Assemblies. Components are assembled for new build, refurbishment, re-purposing and abandonment within Assemblies, as appropriate. Assemblies are the key 'building blocks' of the tool with each Assembly being clearly defined in a technical diagram that gives the element boundary, typical configuration and capacity range.

  The name given to each Assembly includes the following descriptors:

  - Vector: Electricity, Gas, Heat, Hydrogen
  - Function: Transmission, Distribution, Conversion, Connection, Storage
  - Mode: eg. NTS, HP, IP. MP, LP, None
  - Rating: eg 26" gas pipe
  - Installation: Buried, Overhead, Offshore, Tunnelled, None

  This naming structure is used wherever Assemblies are referred to in this report.

- **Projects** are collections of Assemblies with specific quantity multipliers combined to produce whole Project cost estimates. Projects can be attributed with specific context (urban, rural, etc), scale and region to allow Assembly costs to be appropriately modified during calculations.

This study makes use of the Project functionality of the tool. A detailed description of how this works and how the data flows from Component to Assembly to Project is provided in Appendix B.

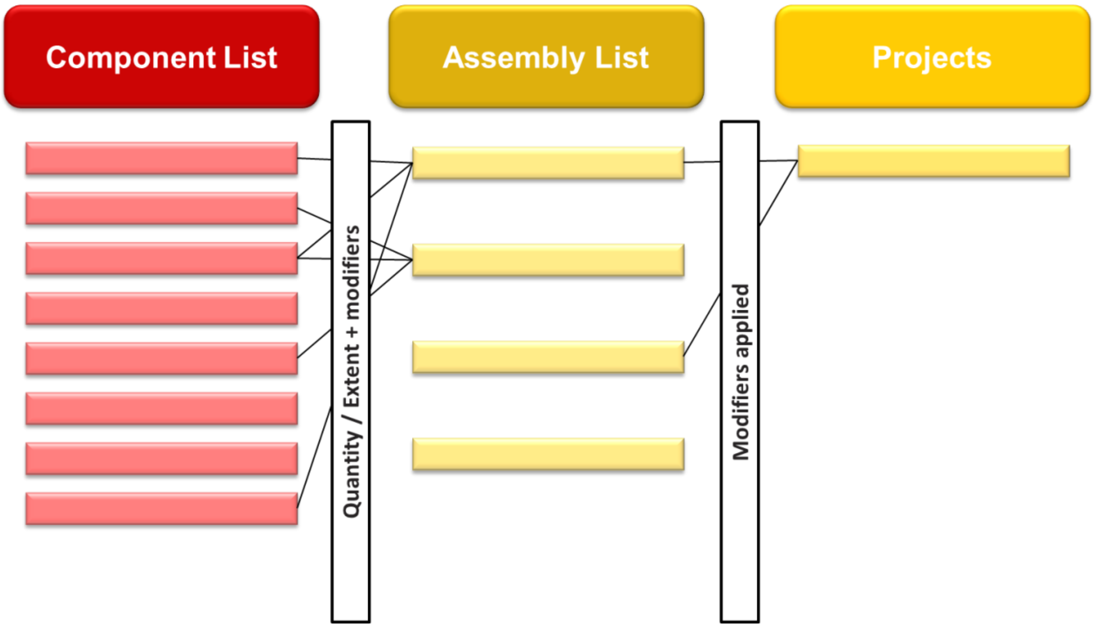


Figure 3-1 Outline of Infrastructure Cost Model structure

3.2.2 Cost data

The approaches to capital and operational costs in the tool are different, primarily due to the difference in availability of data.

Capital costs are derived using a 'bottom up' approach whereby each Component is costed separately as data is generally available at this level. The data has been built up from a number of sources which vary in quality from strong to weak. Items for which data is weakest are generally those which are relatively new and for which there are few precedents. The quality of the data is referenced within the tool.

A more 'top down' approach is used for operational costs, based on regional and / or network wide data that reflects the way that networks tend be managed and reported upon, particularly in the case of the regulated utilities. Operational costs include for direct and indirect costs and are based on the published network costs of the Distribution Network Operators (DNOs)[2]. Profiles for changes in operating costs over time are described in Section 3.2.4 below.

[2] For a full description of how operational costs were applied in the tool, see the *ETI Energy Infrastructure 2050 Final Report*, 22 November 2013, available from the ETI, in particular Chapter 7 and Appendix G, *Opex Framework for Energy Infrastructure*, PPA Energy, April 2013.

3.2.3 Component cost rate modifiers

All Components are given a baseline cost, split into materials, labour and plant. In order to reflect the fact that costs vary in different contexts and under different circumstances, modifications (expressed in percentage changes) to this baseline cost are allowed for. Thus for example, while the baseline cost for civils associated with the installation of 12" LP gas pipeline in a rural context might be £135/m, the ICC assumes that semi-urban costs are 130% of this and urban costs are 400%. Similarly, cost rate modifiers are applied for different scales of installation, and different environments such as ground conditions.

To take account of the variation of costs across the UK, the current version of the ICC applies Regional Tender Price Indices as extracted from Building Cost Information Service (BCIS). Thus for example, the cost of projects installed in London are inflated by 122% against the 'All of UK' baseline.

3.2.4 Operational and lifecycle cost profiles

The ICC recognises that different infrastructure elements are likely to have different cost profiles over time. This is accounted for through the application of different operational cost and lifecycle cost profiles.

- **Operational cost profiles**: The most significant impact on operational costs over an asset's life is the failure rate and therefore the need for reactive maintenance. The failure rate is assumed to be mainly influenced by the asset type, either active or passive. On this basis, two profiles are incorporated into the tool to represent the variation in operating cost over the life of the asset (from 0 to 100% of the defined asset life) as illustrated in Figure 3-2. The area under each profile curve is taken as the total operating cost for the asset over its life and the operating cost in any given year is determined as a proportion of the total operating cost that is applied in that year[3].

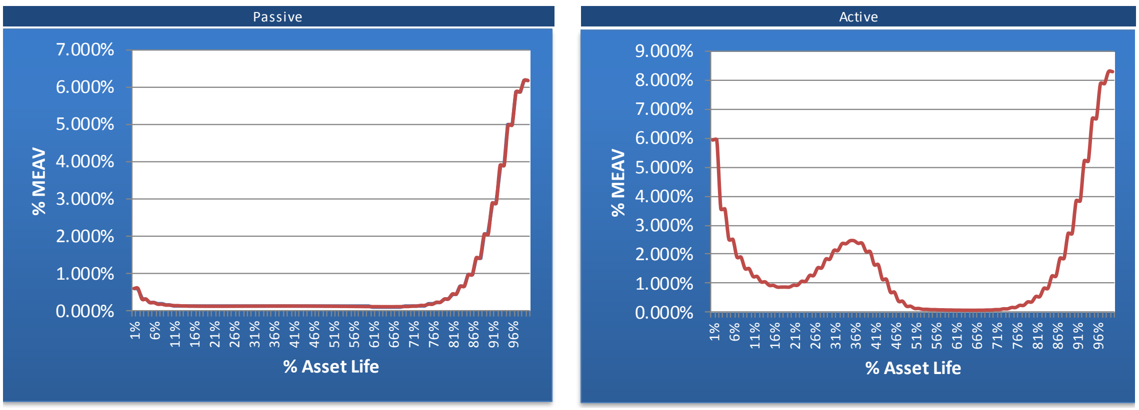


Figure 3-2 Passive and Active Opex profiles in the ICC v1[4]

- **Lifecycle cost profiles**: The lifecycle profile defines the periods of major and minor replacement and the percentage replaced in each of these cycles. It also includes abandonment at end of life. The cycles are deemed to differ according to context (ie assets are assumed to have a shorter lifecycle in an urban context than in a rural one). Two examples of lifecycle profiles used in the tool are shown in Figure 3-3[3].

[3] The modelling of Opex and lifecycle costs will be changed in v2 of the ICC. In v1, Opex comprises failure costs and indirect Opex only, with cyclical replacements of capital equipment and abandonment being modelled through the lifecycle profiles as described here. In v2, the method will use combined Weibull curves to represent failure costs, indirect Opex and replacements of capital equipment, with these latter costs being spread over a number of years, rather than all at once as in v1.
[4] MEAV is the Modern Equivalent Asset Value and is used as the basis for calculating operational costs.

Profile 1: 25 Year asset life

Lifecycle Parameters	% Replaced	Cycle (Years)		
		Short	Baseline	Long
Major Replacement	100%	19	25	38
Minor Replacement	10%	10	13	19
Abandonment		38	50	75
Cycle modifier		Urban	Semi-Urban	Rural
		90%	100%	120%

Profile 2: 40 Year asset life

Lifecycle Parameters	% Replaced	Cycle (Years)		
		Short	Baseline	Long
Major Replacement	100%	30	40	60
Minor Replacement	10%	15	20	30
Abandonment		60	80	120
Cycle modifier		Urban	Semi-Urban	Rural
		90%	100%	120%

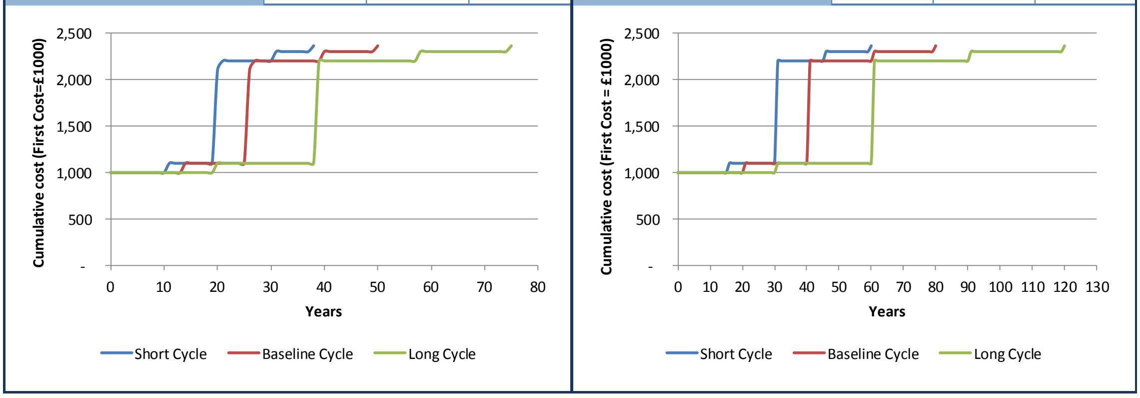


Figure 3-3 Lifecycle profiles in the ICC v1

3.2.5 Trends

The tool includes two specific types of cost trend that are applied to Component data.

The first are general real-term cost trends applied specifically to labour, materials and plant. High, medium and low increase trends are allowed for within the ICC, with the default trend – used in this analysis – being medium (Figure 3-4). Alternative versions of these trends are being developed for future analysis.

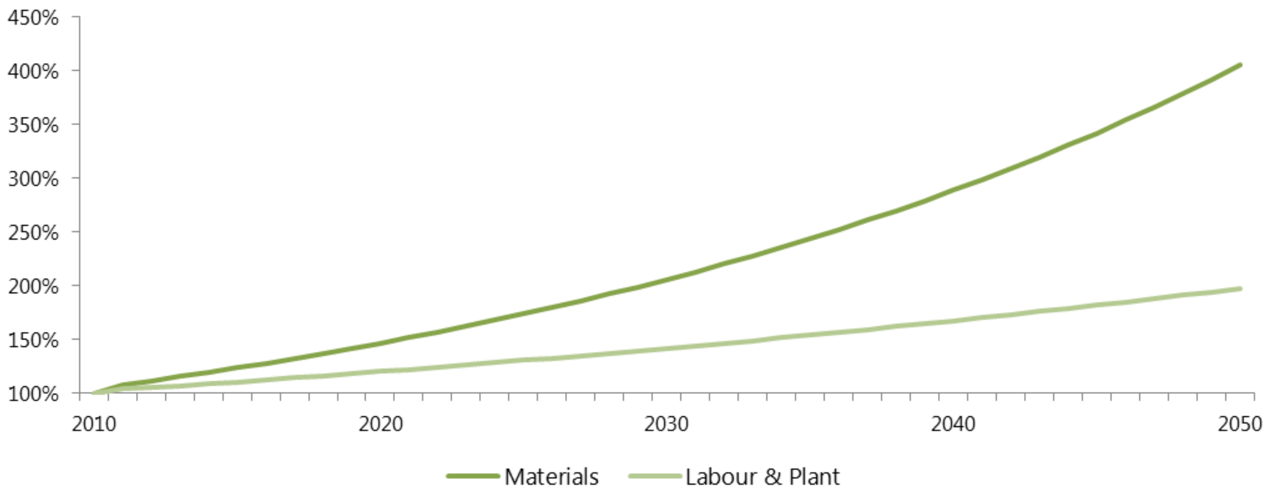


Figure 3-4 Medium general real-term cost trends as applied in the analysis

The second are technology cost curves that relate to the different cost trajectories arising as a consequence of the maturity of the underlying technology. Five curves are available within the ICC as illustrated in Figure 3-5. These are taken from a report prepared by EA Technology for Ofgem[5] and are made up as follows:

Type 1; Rising (based on an average of the Steel and Aluminium cost curves)

Type 2; Flat (to represent no change in cost)

Type 3; Shallow reduction (based on an average of offshore wind farm costs and flat line)

Type 4; Medium reduction (based on the cost curve for offshore wind farms)

Type 5; High reduction (based on the cost curve for laptops)

The majority of Components are categorised as Type 2 (flat) but steeper reduction curves are applied to more innovative technologies.

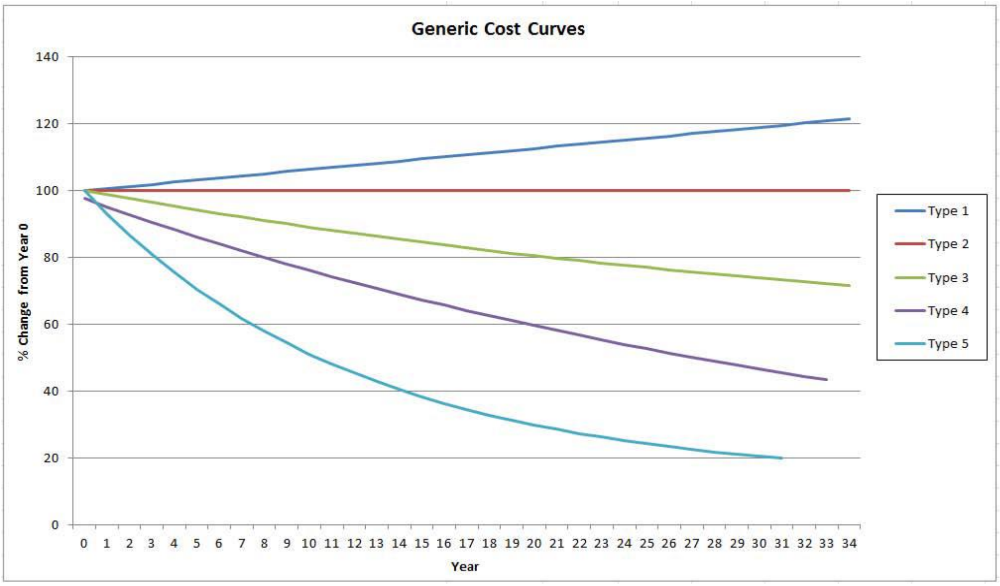


Figure 3-5 Technology cost curves incorporated into the ICC v1

3.2.6 Projects

For the purposes of this study, the key functionality of the tool is the costing of Projects. A Project is essentially a Bill of Quantities (BoQ) based on a specific network design, the BoQ comprising a list of Assemblies each with a particular quantity.

Project costs are built up within the database such that cost data flows from the Components through to the Assemblies and on to the Project. As noted above, the tool allows for baseline costs to be modified according to particular circumstances of installation. Thus for example, different projects may be installed in different ground conditions, or in different contexts (urban, semi-urban, rural) resulting in different out turn costs.

[5] http://www.ofgem.gov.uk/Networks/SGF/Publications/Documents1/WS3%20Ph2%20Report.pdf

A detailed description of how the cost rate modifiers are applied and the data flows from Component to Assembly to Project is provided in Appendix B.

3.3 Application of the ICC in this study

This section outlines how the ICC has been used in this study, describing the treatment of all input variables and the derivation of outputs.

3.3.1 Inputs

As noted above, the ICC allows for a variety of factors to be specified in order to tailor the analysis to the specifics of a particular project. For this study, some of these have been applied specifically for each project while some have been fixed across all projects as a practical response to managing the amount of data generated. A description of each variable is given below.

1. Add on costs (contingencies etc): these are calculated as a percentage of Capex and have been set at the same rate for all projects in this analysis as detailed in Table 3-1.

Table 3-1 Add on costs applied to all projects

Parameter	Description / details	Value
Project management, Engineering, etc	% to be added to Capex	12%
Preliminaries	% to be added to Capex	15%
Contractor overheads and profit	% to be added to Capex	5%
Contingencies	% to be added to Capex	10%

2. Cost trends for labour, materials and plant: all projects use the Baseline trend (see Section 3.2.5).
3. Technology maturity: these are specified at Component level depending on the nature of the Component (see Section 3.2.5).
4. Installation conditions: excavation difficulty, ground contamination and ground water are the same for all projects as outlined in Table 3-2.

Table 3-2 Ground conditions applied to all projects

Parameter	Condition	% of ground in specified condition
Excavation difficulty	Ground is soft and clean. No rock or hard material	60%
	Intermittent rock / hard material (20% by volume)	30%
	Prolific rock / hard material (75% by volume)	10%
Ground contamination	Ground is clean and inert	50%
	Ground is mildly contaminated	30%
	Ground is heavily contaminated	20%
Ground water	Little or no ground water	80%
	Intermittent dewatering required	20%
	Continuous dewatering required	0%

5. Region: all projects (rural, semi-urban and urban) are designated as 'All of UK' with the exception of the London context which is designated as London (see Section 3.2.3).

6. Context: this is a variable within the analysis, thus projects are defined as urban, semi-urban or rural as specified in the relevant Detailed Scoping document.

7. Optimism bias: this is the same for all projects as outlined in Table 3-3.

Table 3-3 Optimism bias applied to all projects

Parameter	Description / details	Value
Optimism bias	% Increase to estimated NPV to allow for Optimism Bias:	Capital Expenditure
	Lower	6%
	Upper	66%

7. Cash flow parameters: these are the same for all projects as outlined in Table 3-4. In particular it is important to note that cash flows are derived for the period 2015 to 2075 (ie a 60 year period) regardless of installation date. Thus a project installed in 2040 will have cash flows over the period 2040 to 2075 and these cash flows will be discounted back to 2015.

Table 3-4 Cash flow parameters applied to all projects

Parameter	Description / details	Value
Start year	This is the date at which the NPV is calculated.	2015
Lifecycle Assessment Period (years)	This is the total period over which project cash flows are assessed.	60
Discount rate	From 2015	3.5%
	From 2046	3.0%

3.3.2 Outputs

The key outputs from the ICC used in the analysis are the Net Present Value (NPV) [6] of the capital and operational costs over the project life; the first cost, being the initial capital cost, undiscounted; and the relative cost of different Assemblies within the network. These are described below.

- **The capital cost NPV** is the NPV of cash flows associated with the initial installation of the asset plus those associated with replacement and abandonment. Cash flows are initially discounted at 3.5% and at 3.0% from 2046.

[6] Note, throughout this report, the term Net Present Value (NPV) has been used to refer to discounted cash flows as this is a convention as used in the ICC. However, it should be noted that as all cash flows are in fact costs (ie no 'values' or revenues are included), strictly the term should be Net Present Cost.

An example of these cash flows is illustrated in Figure 3-6. This graph is an output of the tool and shows the annual cash flows associated with capital and replacement costs for a new build hydrogen distribution network including pipes, conversion stations and connections. The project assumes all assets are installed in 2020, with subsequent cash flows associated with minor and major replacement cycles occurring periodically thereafter. As noted in Section 3.2.4 above, the minor and major replacement cycles are determined by the lifecycle profile attributed to the Assemblies in the project as annotated in the graph below.

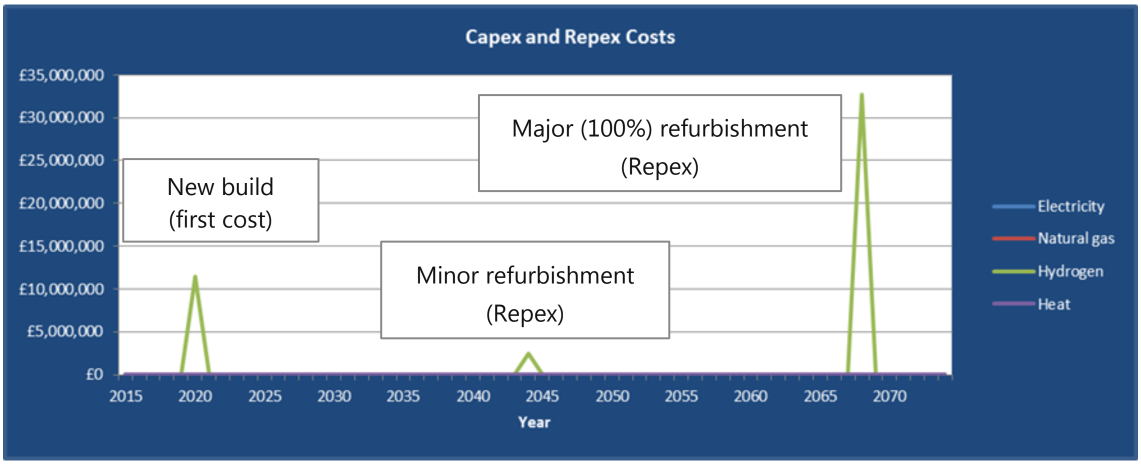


Figure 3-6 Graphical output from ICC showing capital and replacement cost cash flows over the life of a project with assets installed in 2020

An important point to take into account in the interpretation of the results in this report is the impact on lifecycle costs of deferring installation. Thus, if the same network shown above were installed in 2040 rather than 2020, the lifecycle cash flows would be as illustrated in Figure 3-7. The new build costs are now in 2040 and are higher than in 2020 due to the impact of inflation (Figure 3-4) with the minor refurbishment occurring in 2064. However, as the period for calculating the NPV is fixed at 60 years from 2015, the major replacement is beyond the end of the assessment period and therefore not included in the cash flow. This can have a significant impact on NPV when comparing costs at different installation dates.

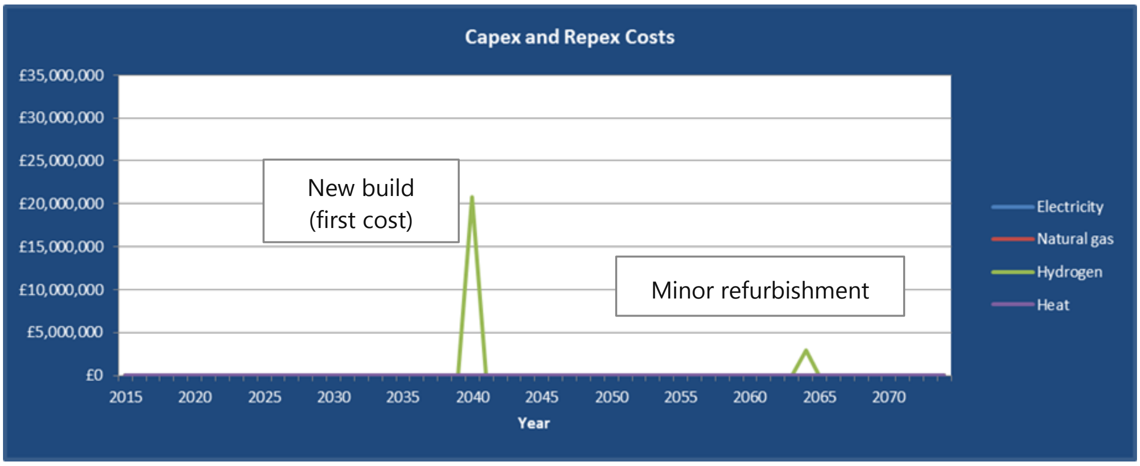


Figure 3-7 Graphical output from ICC showing capital and replacement cost cash flows over the life of a project with assets installed in 2040

- **The opex NPV** is the NPV of all operational cost cash flows associated with all Assemblies in the Project over the assumed project life.

  An example of these cash flows is illustrated in Figure 3-8. This graph is an output of the tool and shows the annual cash flows associated with operational costs for a new build hydrogen distribution network including pipes, conversion stations and connections. As noted in Section 3.2.4 above, operational costs are determined by the operational cost profile attributed to the Assemblies in the project.

Figure 3-8 Graphical output from ICC Cost Tool showing operational cost cash flows over the life of a project

- **First cost** is the undiscounted cost of the initial installation of the asset including preliminaries and contingencies etc. but without considering replacement and abandonment. This has been included in the analysis to contextualise costs excluding Repex and Opex. First costs are higher at later installation dates due to the impact of the future cost trends (see Figure 3-4.

- **Relative cost of Assemblies:** The analysis also explores the relative costs of different Assemblies within a network to understand key cost drivers. The costs being compared are the total undiscounted costs of all Capex and Repex associated with that Assembly over the project life.

3.4 Considerations and limitations

The cost outputs of the tool and thus the analysis arising need to be viewed with the following issues in mind:

- Technical scope

  As noted above, the key units or 'building blocks' in the tool are the Assemblies. Each Assembly is defined so as to be representative in terms of configuration, capacity, size etc of a 'typical' piece of infrastructure. Given the wide number of alternative designs and configurations available in practice, it is recognised that selecting a single 'typical' design reduces the accuracy of a detailed study. For the purposes of this high level study however, the designs within the tool are considered to be adequate. Where no appropriate Assembly was available in the tool for a particular research question, a new one was added.

- Opex

  The approach taken to operational costs was simplified for the purposes of this first version of the tool. These are being refined for the second version.

- Losses

  No account is taken of losses occurring over the network. Losses were not included in the tool due to their dependence on network design, which is outside the scope of the tool.

- Lifecycle profiles

  Three lifecycle profiles are included in the tool, all of which include for a major (100%) replacement after a certain period. The inclusion of lifecycle costs in the Capex NPV influences results particularly where installation occurs at different dates given that the assessment period remains fixed (ie 60 years from 2015 to 2075).

  It should be noted that the modelling of lifecycle costs will be revised in the next version of the tool, taking a more probabilistic approach and thereby allowing for cash flows to be smoothed. In addition, lifecycle costs will be included in with Opex costs rather than with Capex costs.

- Project cost parameters

  The tool allows for the variation of a number of different parameters in relation to ground conditions, prelims costs, optimism bias etc. For the purposes of this initial study, these have been fixed for all projects. They can however be varied should more detailed analysis be required at a later date.

- Economic trends

  Subsequent to the initiation of this project, the economic trends for materials, labour and plant costs have been revised. These revisions have not been taken into account in this analysis.

Overall, the results of the analysis need to be considered in the context of the first version of the ICC. As well as providing cost information for ETI research teams, the exercise has also identified issues to be addressed in the second version of the tool.

4 H2-G-21 Representative Hydrogen Transmission Model (power generation and transport refuelling sites)

4.1 Research question overview and scope

This analysis is intended to provide the costs of a reference hydrogen transmission network connecting hydrogen production facilities in rural areas. Two alternative scenarios are explored, connecting to power generation and connecting to transport refuelling sites.

The schematic Figure 4-1 shows the boundary and network layout of each scenario. In the context of the ICC, the Assemblies used to build the network are:

Power generation:

- Transmission: NTS: Buried: 32" Hydrogen Pipe 29,000,000 m^3/day

Refuelling stations:

- Distribution: HP: Buried: 16" Hydrogen Pipe - 12,000,000 m^3/day
- Conversion: NTS: Above Ground: NTS Hydrogen Compressor Station 12,000,000 m^3/day

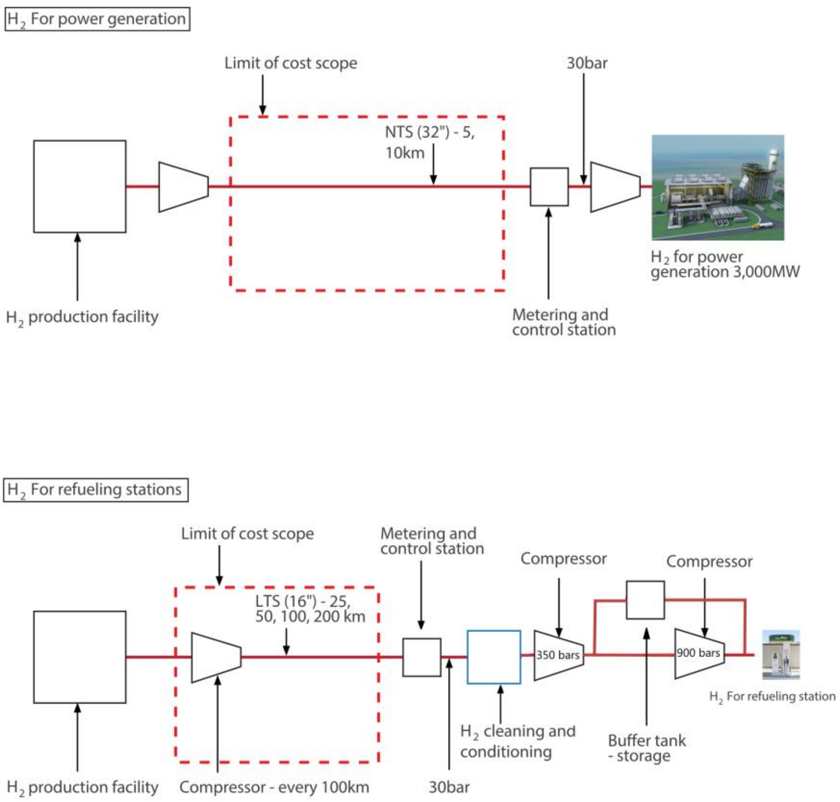


Figure 4-1 Network schematic indicating scope boundary

Compression stations are only required for pipe lengths of 100km or longer and therefore are only included in the transport refuelling station variants with network lengths of 100km and 200km. It is assumed that the H_2 production facility generates H_2 at sufficient pressure for distances less than 50km.

Table 4-1 gives the variations of installation date, capacity, pipe length and context to be applied to each project.

Table 4-1 Project variants

H_2 to power generation		
Parameter	**Variants**	**Application**
Installation date	2025 2050	Each date applied to each of the other variants
Capacity / pipe diameter	NTS – 32"	Single capacity
Context	Rural	Single context only
Length	5, 10km	Each length applied to each of the other variants
Mode	New build	All costs new build
H_2 to refuelling stations		
Parameter	**Variants**	**Application**
Installation date	2025 2050	Each date applied to each of the other variants
Capacity / pipe diameter H_2 compressor station	LTS – 16" H_2 compressor station for distances over 100km only	Single capacity Single capacity
Context	Rural	Single context only
Length	25, 50, 100, 200km	Each length applied to each of the other variants
Mode	New build	All costs new build

4.2 Results and analysis

Based on the variants in Table 4-1, 12 cost data sets were generated using the ICC (4 for H_2 power generation and 8 for H_2 refuelling stations). Each data set is representative of a different variation.

NPV and first costs have been calculated as shown in Table 4-2. These results are presented in Figure 4-2. As discussed in Section 3.3.2, first costs (undiscounted) include new build costs plus preliminary costs, contractors costs, PM engineering, land costs and contingencies but exclude any lifecycle replacement costs; NPV Capex represents the installation costs plus all lifecycle costs (which include all replacement cycles and abandonment costs - Repex – to the extent that these occur before the project end); and NPV Opex takes into account operational costs over the life of the project.

Table 4-2 Base output data

Hydrogen use	Installation date	Pipe length (km)	First cost (£m)	NPV Capex (£m)	NPV Opex (£m)	NPV total (£m)
Power generation	2025	5	19.3	23.2	3.6	26.8
		10	38.7	46.4	7.1	53.6
	2050	5	40.0	14.6	1.5	16.1
		10	80.1	29.2	3.1	32.2
Refuelling stations	2025	25	58.8	66.9	10.9	77.8
		50	112.6	128.0	20.9	148.9
		100	260.8	297.0	49.1	346.1
		200	483.5	550.4	90.9	641.4
	2050	25	123.1	44.8	4.7	49.6
		50	235.3	85.8	9.0	94.8
		100	551.0	200.2	21.3	221.4
		200	1,020.7	371.5	39.4	410.9

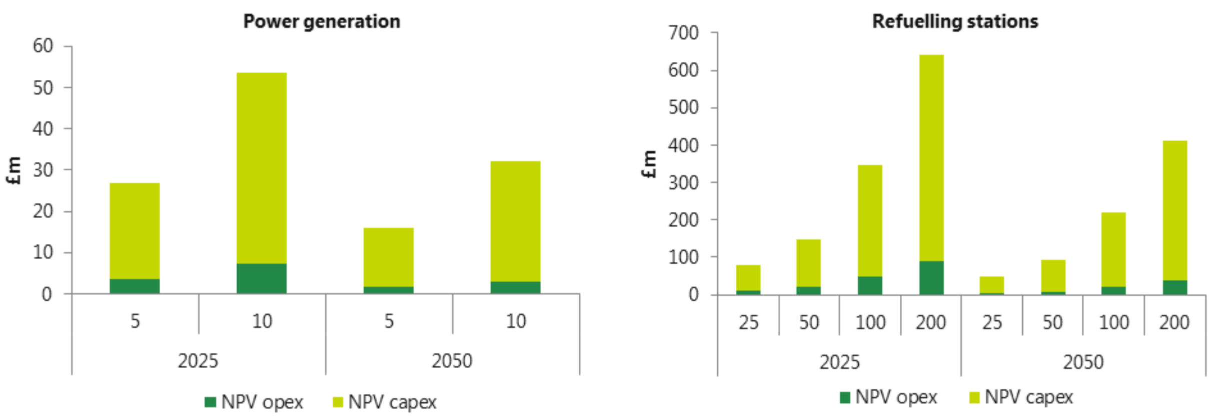


Figure 4-2 NPV (Capex and Opex) for the two scenarios

Key findings:

- First costs are higher at later installation dates due to the indexation applied in the tool (see Section 3.2.5).
- NPVs are lower for later installation dates. This is partly due to the effects of discounting and partly due to the 40-year life cycle applied to the pipework Assemblies, which means that in the 2050 variation the major refurbishment cycle is beyond the end of the assessment period.

- The ratio of Capex to Opex remains relatively consistent across all variants (Capex ranges from 86-90% of total NPV). Labour, material and maintenance costs increase linearly with pipe length.
- As expected the greater the distance, the greater the costs. See the normalised cost analysis in Section 4.2.2.
- Power generation projects as modelled here have significantly lower costs compared with refuelling station projects. Projects in which vehicle refuelling is end-use of the hydrogen require significantly longer pipework. In addition, projects with pipe lengths of 100km or above require a compression station that further increases costs. See the normalised cost analysis in Section 4.2.2 for more details.

4.2.1 Analysis: Assemblies

Power generation projects require pipe lengths below 100km (5 and 10km are modelled here) and therefore do not require compressor stations, meaning only transmission Assemblies apply which therefore constitute 100% of assembly costs for these projects.

Refuelling station projects with 25-50km of piping also do not require compressor stations, meaning only distribution Assemblies apply and therefore constitute 100% of assembly costs for these projects.

Refuelling station projects with 100km piping and above require both distribution Assemblies and compressor stations (1 every 100km). The split of these costs remains relatively consistent across the two installation dates (2025-2050) and pipe lengths (100-200km), with distribution Assemblies (HP buried 16") representing 75-78% of total assembly costs versus the compressor station at 22-25% of the total.

4.2.2 Analysis: Normalised costs

Table 4-3 gives normalised costs for each variation. These results are presented in Figure 4-3 and Figure 4-4.

Table 4-3 Normalised costs output data

Hydrogen use	Installation date	Pipe length (km)	First costs per km (£m/km)	NPV per km (£m/km)
Power generation	2025	5	3.9	5.4
		10	3.9	5.4
	2050	5	8.0	3.2
		10	8.0	3.2
Refuelling stations	2025	25	2.4	3.1
		50	2.3	3.0
		100	2.6	3.5
		200	2.4	3.2
	2050	25	4.9	2
		50	4.7	1.9
		100	5.5	2.2
		200	5.1	2.1

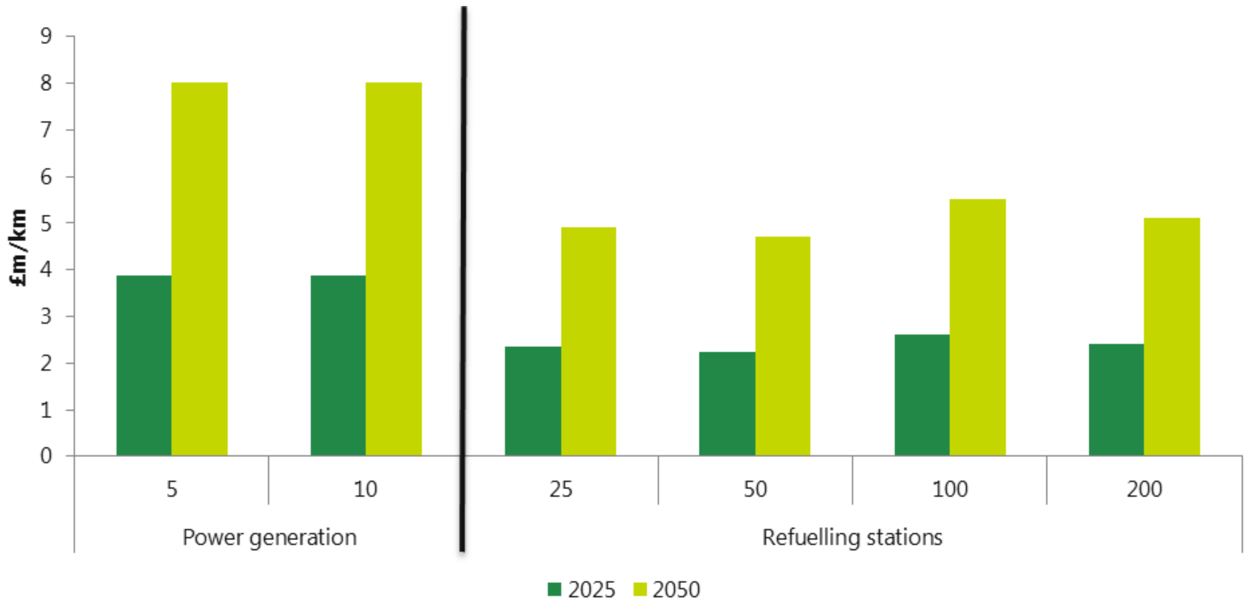


Figure 4-3 First costs per km

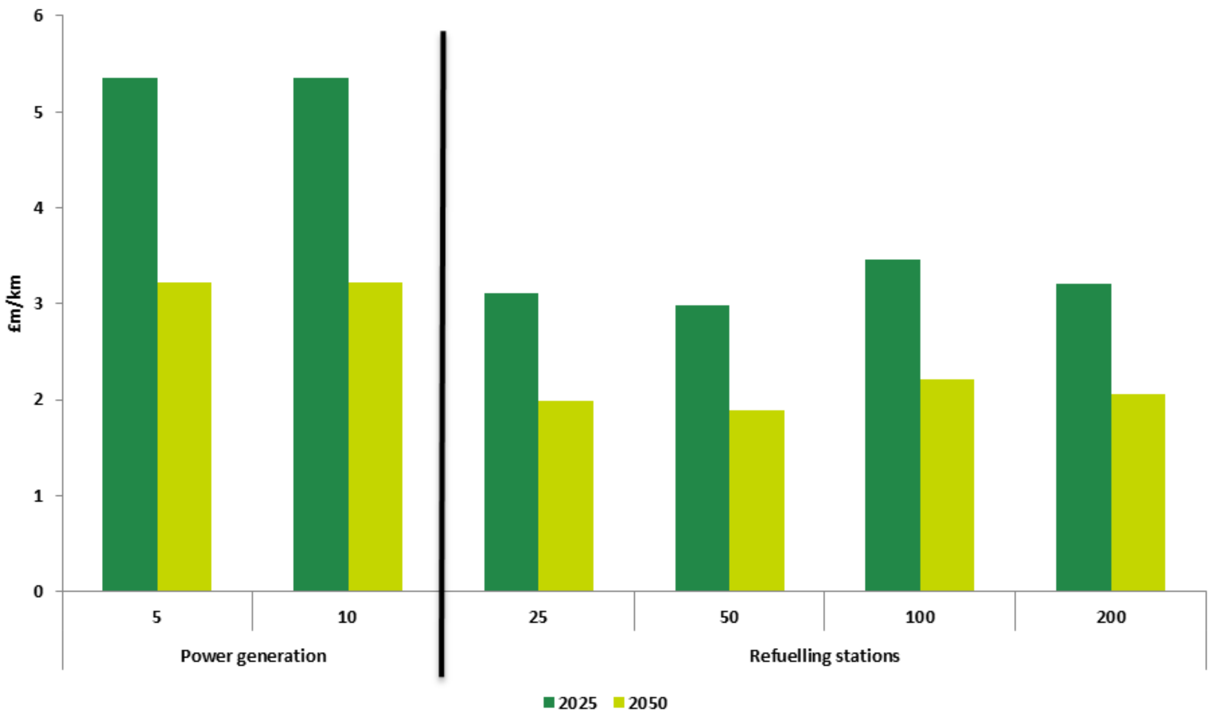


Figure 4-4 NPV cost per km

Key findings:

- Both NPV total and first costs per km are much higher for the power generation variants compared with those for transport refuelling sites. Power generation variants are around 40% more expensive than transport refuelling sites. This is mainly due to the higher cost of the NTS transmission infrastructure (32”) compared with the distribution (16”) network.
- In general, for transport refuelling sites there is a reduction in cost per km for each additional km of piping. There is no cost difference per km between 5km and 10km, this may be due to the small pipeline length variation – this is to be further analysed in due course. Both normalised NPV total and first costs increase slightly from 50km to 100km due to the addition of the compressor station in the 100km variant.
- For the power generation variants, the normalised costs remain the same for additional km of piping. This may be due to the relatively short pipe length considered (5km and 10km).

4.3 Limitations and further work

The limitations highlighted in the Detail Scoping also have an impact on the accuracy of the cost analysis. Specifically:

- The cost analysis does not include losses which would impact on lifecycle costs. However, losses would be minimal in new build infrastructure.
- Further investigation of the impact of the scale rate modifiers in the ICC could be explored.

As noted in Section 3.4, there are a number of considerations to be taken into account in relation to the design and modelling assumptions contained in first version of the ICC. In particular, cost trends and the treatment of Opex and lifecycle costs are to be revised in the second version of the tool which could impact on these results.

5 H2-G-22 Representative Hydrogen Distribution Model (transport refuelling sites)

5.1 Research question overview and scope

This analysis is intended to provide a reference hydrogen distribution network cost in rural, semi-urban, urban and London areas for connection to new transport refuelling sites.

The schematic Figure 5-1 shows the boundary and network layout of this project. In the context of the ICC, the Assemblies used are:

- Distribution: MP: Buried: 6" Rural Hydrogen Pipe 87,000 m^3/day
- Distribution: MP: Buried: 6" Urban Hydrogen Pipe Only 348,000 m^3/day
- Conversion: Above Ground: Hydrogen compressor with storage tank with two capacities: 170,000 m^3/day and 340,000 m^3/day

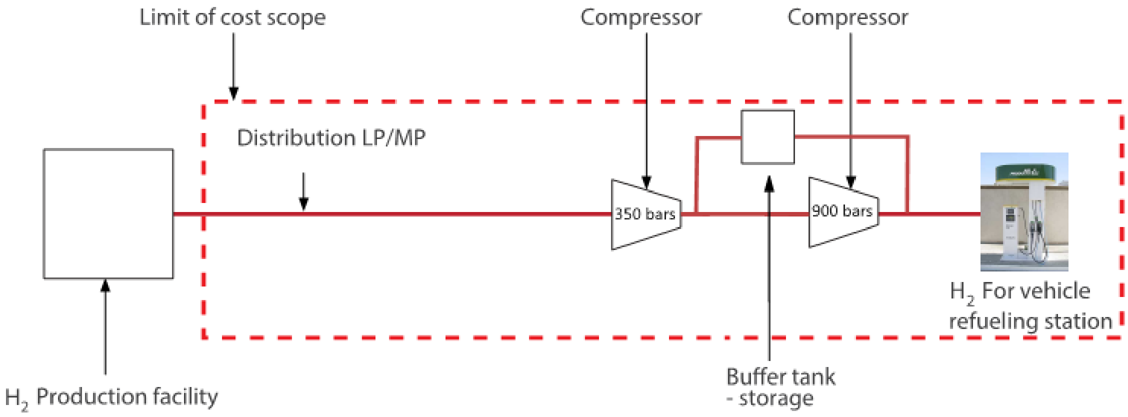


Figure 5-1 Network schematic indicating scope boundary

The MP 6" pipeline is considered sufficient for the capacity range selected for this task (42,500Nm^3/day – 340,000Nm^3/day).

Table 5-1 gives the variations of installation date, capacity, pipe length and context assessed in the analysis.

Table 5-1 Project variants

Parameter	Variants	Application
Installation date	2025 2050	Each date applied to each of the other variants
Capacity[7]	170,000 Nm^3/day 340,000 Nm^3/day	Each capacity applied to each of the other variants
Context (and length)	Rural, semi-urban: 30 km Urban: 10km London: 1km	Single length applied to each context as indicated
Mode	New build	All costs new build

5.2 Results and analysis

Based on the variants in Table 5-1, 16 cost data sets were generated using the ICC. Each data set is representative of a different variation. The project cost parameters have remained unchanged in each variation.

NPV and first costs have been calculated as shown in Table 5-2. These results are presented in Figure 5-2 and Figure 5-3. As discussed in Section 3.3.2, first costs (undiscounted) include new build costs plus preliminary costs, contractors costs, PM engineering, land costs and contingencies but exclude any lifecycle replacement costs; NPV Capex represents the installation costs plus all lifecycle costs (which include all replacement cycles and abandonment costs - Repex – to the extent that these occur before the project end); and NPV Opex takes into account operational costs over the life of the project.

[7] Note that in the Detailed Scoping, three capacities were proposed. These have been reduced to two on the basis of market availability of the H_2 compressor-storage assembly.

Table 5-2 Base output data

Context	Date	Capacity (Nm3/day)	Pipe length (km)	First Cost (£m)	NPV Capex (£m)	NPV Opex (£m)	NPV Total (£m)
Rural	2025	170,000	30	63.16	69.42	12.20	81.62
	2050	170,000	30	135.39	48.47	5.28	53.75
	2025	340,000	30	67.59	75.73	13.09	88.81
	2050	340,000	30	145.20	52.14	5.67	57.80
Semi-urban	2025	170,000	30	78.57	91.54	15.11	106.64
	2050	170,000	30	168.01	62.46	6.54	69.00
	2025	340,000	30	83.22	98.67	16.04	114.72
	2050	340,000	30	178.30	66.33	6.95	73.28
Urban	2025	170,000	10	74.36	91.29	14.37	105.66
	2050	170,000	10	159.51	61.41	6.22	67.63
	2025	340,000	10	79.23	100.79	15.34	116.13
	2050	340,000	10	170.30	67.14	6.65	73.79
London	2025	170,000	1	16.36	25.20	3.21	28.41
	2050	170,000	1	35.57	16.01	1.40	17.40
	2025	340,000	1	22.31	36.79	4.41	41.19
	2050	340,000	1	48.73	23.01	1.92	24.93

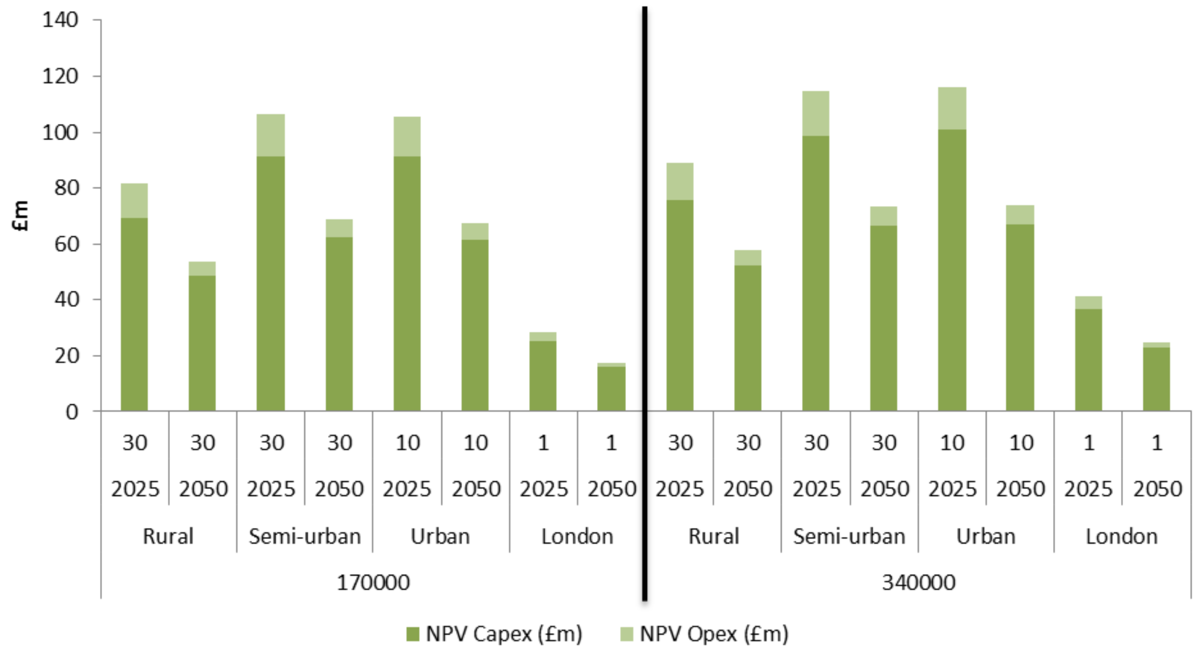


Figure 5-2 NPV Capex and Opex

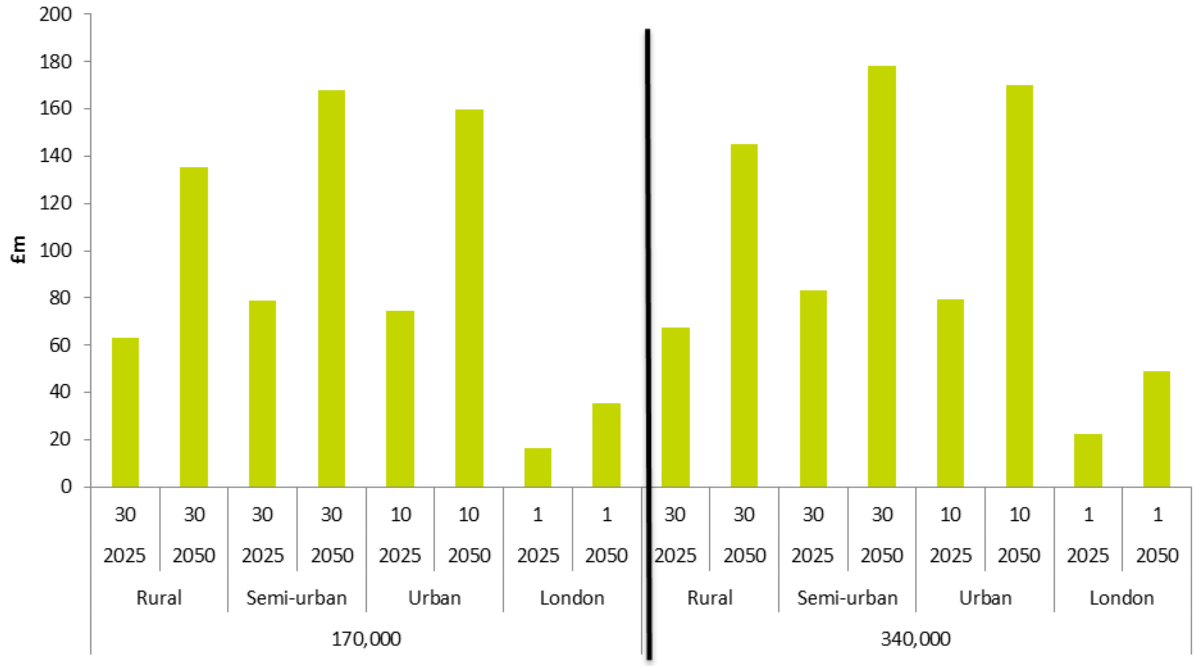


Figure 5-3 First costs

Key findings:

- First costs are higher at later installation dates due to the indexation applied in the tool (see Section 3.2.5).
- NPVs are lower for later installation dates. This is partly due to the effects of discounting and partly due to the 40-year life cycle applied to the pipework Assemblies, which means that in the 2050 variation the major refurbishment cycle is beyond the end of the assessment period.
- The NPV costs for rural/semi-urban 30km is similar to urban 10km. This is due to the higher costs in urban contexts. In general, the direct comparison between contexts for this task is not relevant as different pipe lengths have been considered for each context.
- The higher the capacity for the compressor/storage assembly the higher the costs. For rural, semi-urban and urban there is an increase in cost of 5-10% for the higher capacity (340,000Nm^3/day). For the London context, the increase is more significant being around 30%. This is mainly due to the compressor being a much higher proportion of the costs.

5.2.1 Analysis: Assemblies

As previously stated, two Assemblies have been used for this task: the distribution gas network (MP) and the compressor/storage station. Figure 5-4 to Figure 5-7 illustrate the contribution (in %) from the two Assemblies for each variation.

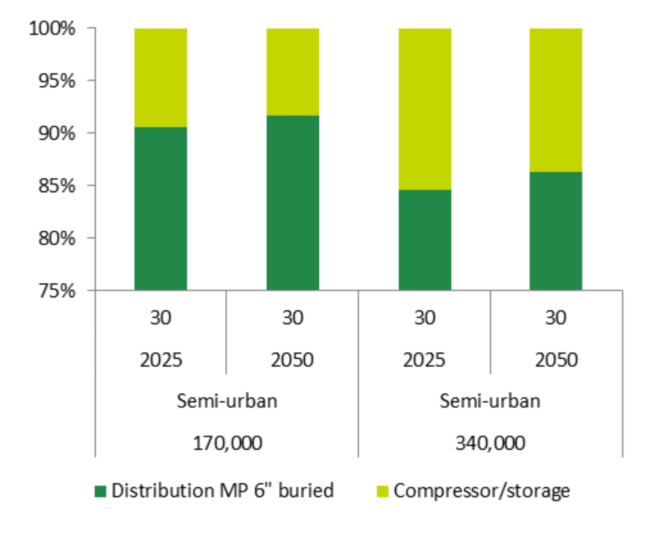


Figure 5-4 % Assemblies NPV costs contribution - Rural

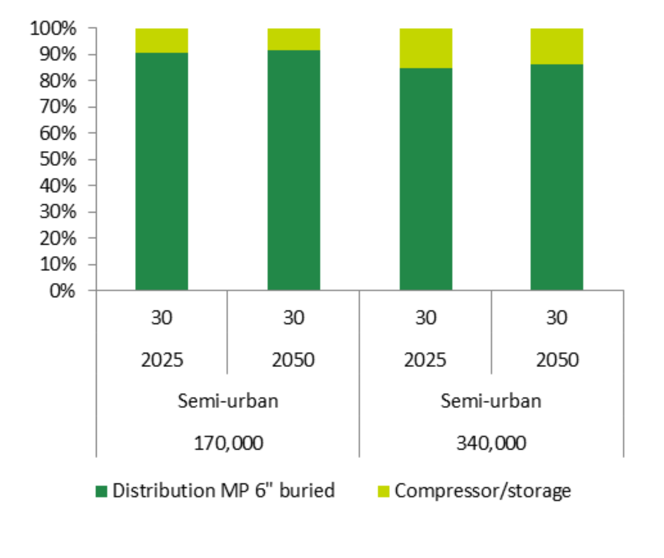


Figure 5-5 % Assemblies NPV costs contribution - Semi-urban

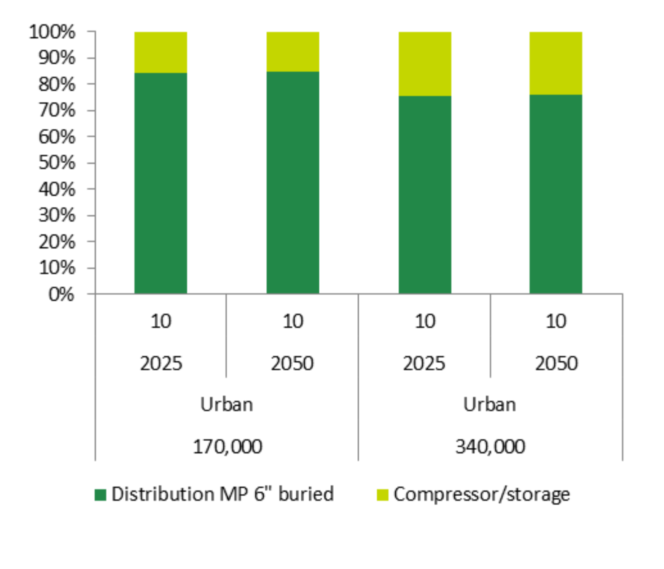


Figure 5-6 % Assemblies NPV costs contribution - Urban

Figure 5-7 % Assemblies NPV costs contribution - London

Key findings:

- For rural, semi-urban and urban contexts the highest contribution to total cost is made by the distribution MP 6" pipework. For rural and semi-urban contexts the pipework represents around 83-92% of the total while in an urban context it is around 75-84%. It is lower in urban areas because, although the unit installation costs are higher, the network length is lower.
- For London, the compressor storage represents the highest percentage of the total costs at 63-76%. This is due to the shorter distance considered for this context (1km).

- The higher the capacity for the compressor/storage assembly, the higher the cost contribution of this assembly.
- The proportion of the cost of different Assemblies remains the same in 2025 and 2050.

5.2.2 Analysis: Normalised costs

Table 5-3 gives normalised costs for each variation. These results are presented in Figure 5-8and Figure 5-9.

Table 5-3 Normalised costs output data

Context	Date	Capacity (Nm3/day)	Pipe length (km)	First cost £m/km	NPV total £m/km
Rural	2025	170,000	30	2.11	2.72
	2050	170,000	30	4.51	1.79
	2025	340,000	30	2.25	2.96
	2050	340,000	30	4.84	1.93
Semi-urban	2025	170,000	30	2.62	3.55
	2050	170,000	30	5.60	2.30
	2025	340,000	30	2.77	3.82
	2050	340,000	30	5.94	2.44
Urban	2025	170,000	10	7.44	10.57
	2050	170,000	10	15.95	6.76
	2025	340,000	10	7.92	11.61
	2050	340,000	10	17.03	7.38
London	2025	170,000	1	16.36	28.41
	2050	170,000	1	35.57	17.40
	2025	340,000	1	22.31	41.19
	2050	340,000	1	48.73	24.93

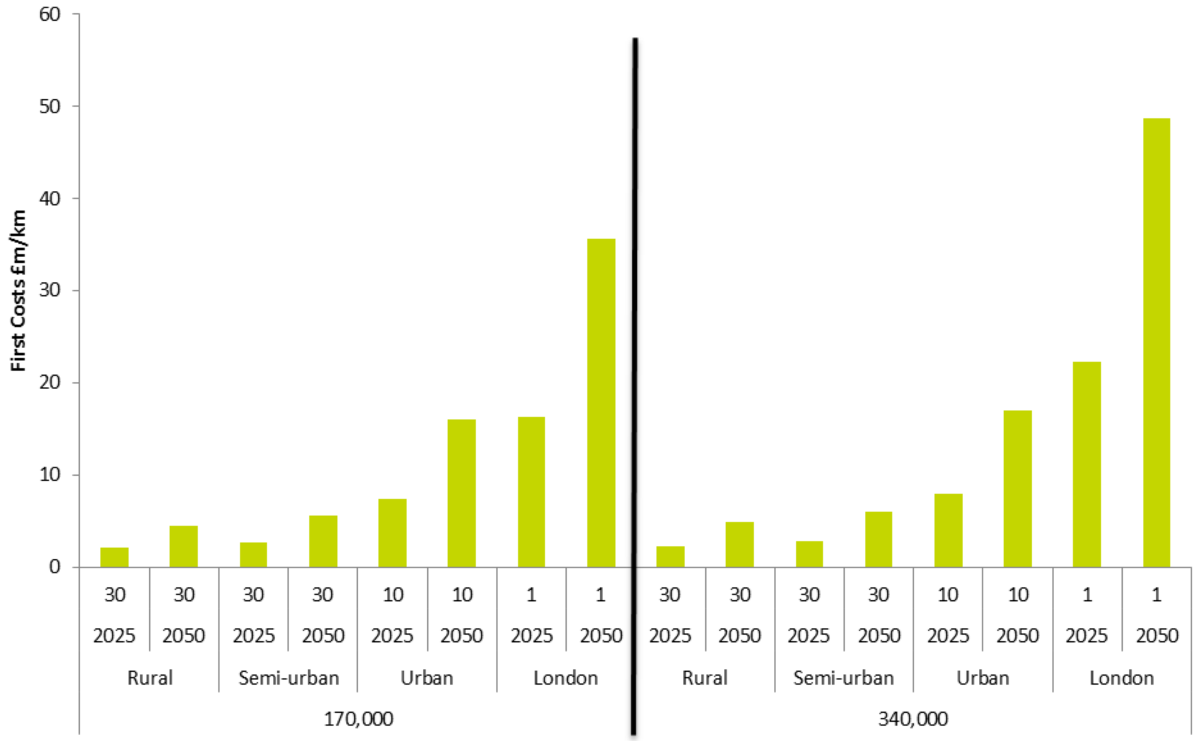


Figure 5-8 First costs per km

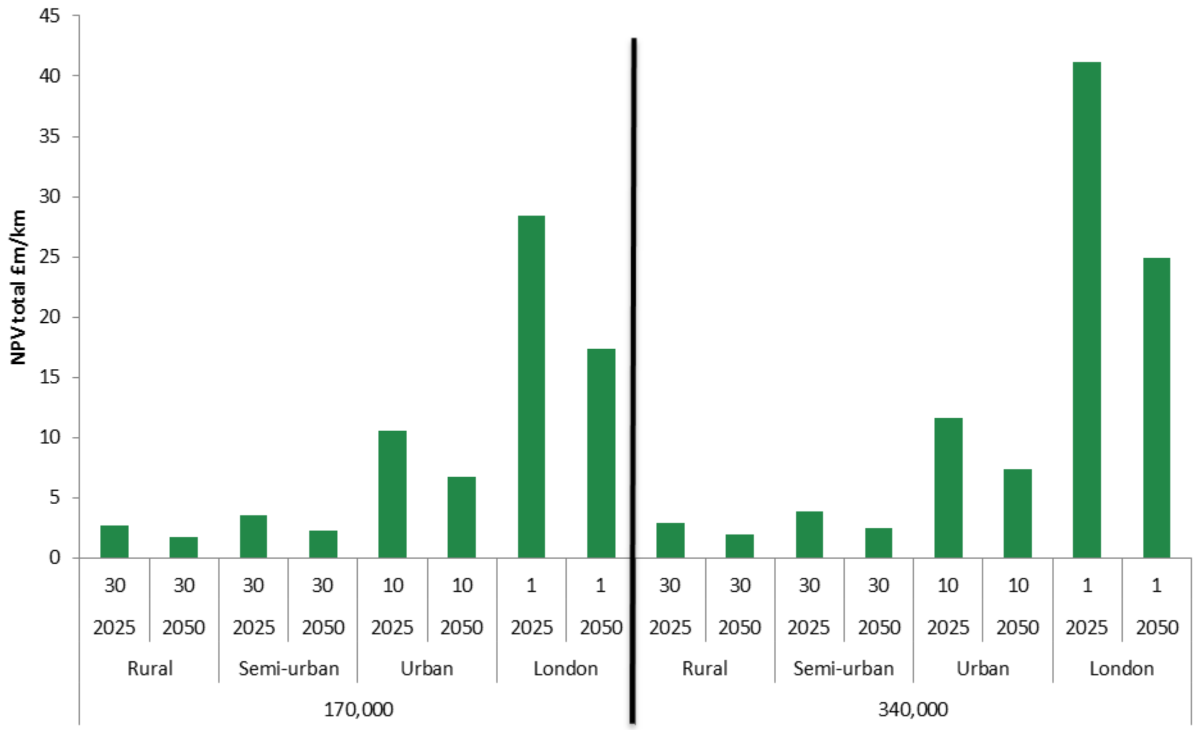


Figure 5-9 NPV cost per km

Key findings:

- Both NPV total and first costs per km increase as the density of the area increases. This is due to the increased cost of installing pipework in more congested urban areas and that overall cost are spread over a shorter pipe length.
- As expected, first costs per km are higher in 2050 than 2025 as the costs in later years are subject to indexation while NPV costs per km are higher in 2025 than 2050.
- In general, there is a minor increase in cost per km for higher capacity of the compressor/storage assembly.

5.3 Limitations and further work

The limitations highlighted in the Detail Scoping also have an impact on the accuracy of the cost analysis. Specifically:

- The cost analysis does not include losses which would impact on lifecycle costs. However, losses would be minimal in new build infrastructure.

As noted in Section 3.4, there are a number of considerations to be taken into account in relation to the design and modelling assumptions contained in first version of the ICC. In particular, cost trends and the treatment of Opex and lifecycle costs are to be revised in the second version of the tool which could impact on these results.

6 H2-I-23 Hydrogen transmission network – impact of including storage

6.1 Research question overview and scope

This research question was concerned with the impact of including different sizes and numbers of large scale storage sites on hydrogen network costs. The analysis was undertaken in the context of power generation and considers two alternative scenarios, one with a single large storage site and one with eight smaller storage sites. These scenarios are compared with each other and with a counterfactual in which no storage is included. All scenarios are at transmission level in a rural context.

The schematic in Figure 6-1 shows the boundary and network layout of each scenario. In the context of the ICC, the Assemblies included in the networks are:

- Distribution: HP: Buried: 20" Hydrogen Pipe 15,000,000 m^3/day
- Storage: None: Salt Cavern storage. Two capacities 60,000,000 m^3 and 460,000,000 m^3
- Transmission: NTS: Buried: 32" Hydrogen Pipe 29,000,000 m^3/day

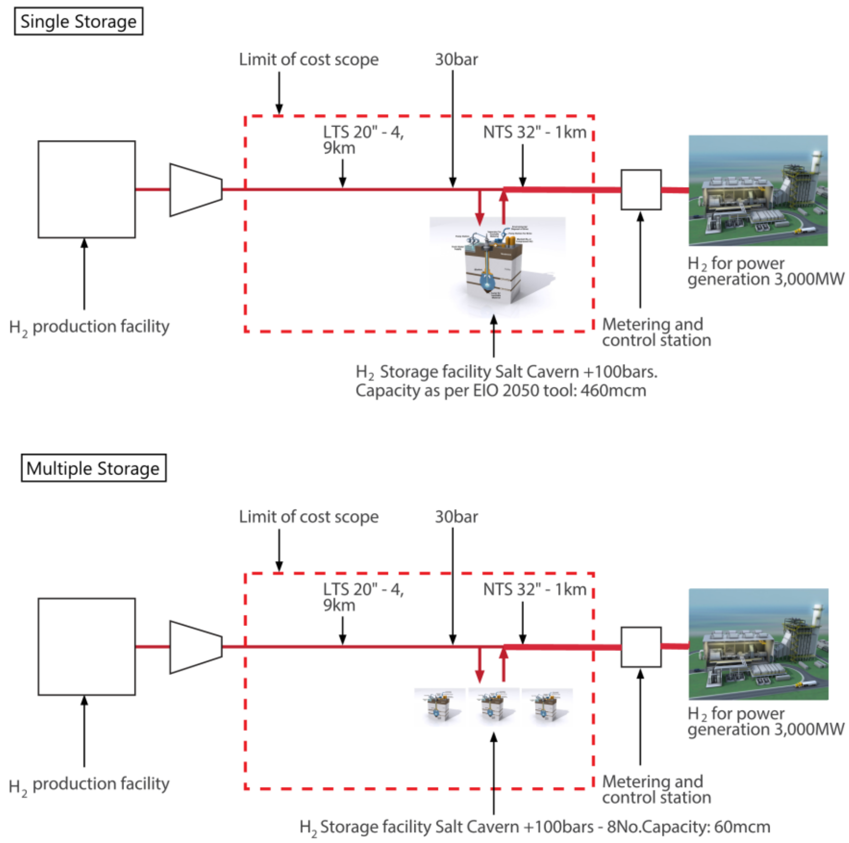


Figure 6-1 Network schematic indicating scope boundary

Table 6-1 gives the variations of installation date, storage type, pipe length and context used in the analysis.

Table 6-1 Project variants

Innovation: single and multiple storage					
Parameter	**Variants**	**Application**			
Installation date	2025 2050	Each date applied to each of the other variants			
Pipe diameter / storage capacity	20” LTS, 32” NTS / 460 mcm x 1 unit 20” LTS, 32” NTS / 60 mcm x 8 units	Each capacity applied to each of the other variants			
Context	Rural	Single context only			
Length	4, 9km – 20” LTS 1km – 32” NTS	Each length applied to each of the other variants			
Mode	New build	All costs new build			
Counterfactual: non-storage					
Description	**Application**	**Mode**	**Quantity**	**Unit**	**Date**
Transmission: NTS: Buried: 32” Hydrogen Pipe [29,000,000m^3/day]	Single application as counterfactual to storage options	New build	5, 10	km	2025 2050

6.2 Results and analysis

Based on the variants in Table 6-1, 12 cost data sets were generated using the ICC. Each data set is representative of a different variation.

NPV and first costs have been calculated as shown in Table 6-2. These results are presented in Figure 6-2 and Figure 6-3. As discussed in Section 3.3.2, first costs (undiscounted) include new build costs plus preliminary costs, contractors costs, PM engineering, land costs and contingencies but exclude any lifecycle replacement costs; NPV Capex represents the installation costs plus all lifecycle costs (which include all replacement cycles and abandonment costs - Repex – to the extent that these occur before the project end); and NPV Opex takes into account operational costs over the life of the project.

Table 6-2 Base output data

Type / Storage	Date	Distance (km)	First Cost (£m)	NPV Capex (£m)	NPV Opex (£m)	NPV Total (£m)
Single storage	2025	5	1,206	1,377	228	1,605
Single storage	2050	5	2,514	894	98	992
Single storage	2025	10	1,220	1,392	231	1,623
Single storage	2050	10	2,542	904	99	1,003
Multiple storage	2025	5	2,035	2,313	383	2,695
Multiple storage	2050	5	4,203	1,494	164	1,658
Multiple storage	2025	10	2,049	2,328	385	2,713

Type / Storage	Date	Distance (km)	First Cost (£m)	NPV Capex (£m)	NPV Opex (£m)	NPV Total (£m)
Multiple storage	2050	10	4,231	1,504	165	1,669
Non - storage/Counterfactual	2025	5	19	23	4	27
Non - storage/Counterfactual	2025	10	39	46	7	54
Non - storage/Counterfactual	2050	5	40.0	15	1.5	16
Non - storage/Counterfactual	2050	10	80	29	3	32

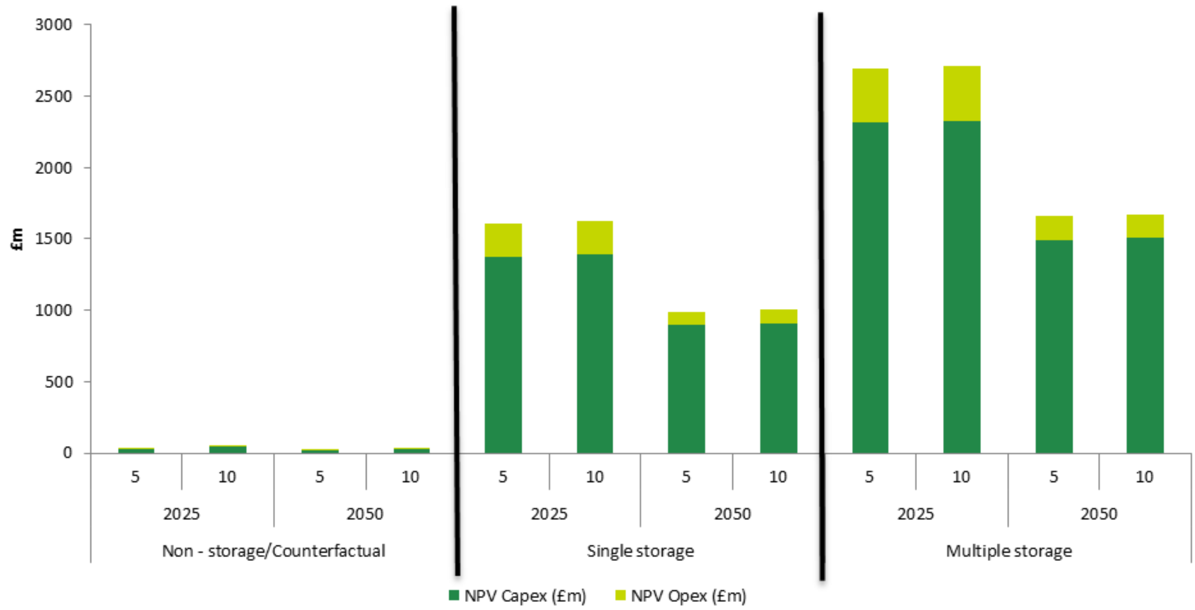


Figure 6-2 NPV Capex and Opex

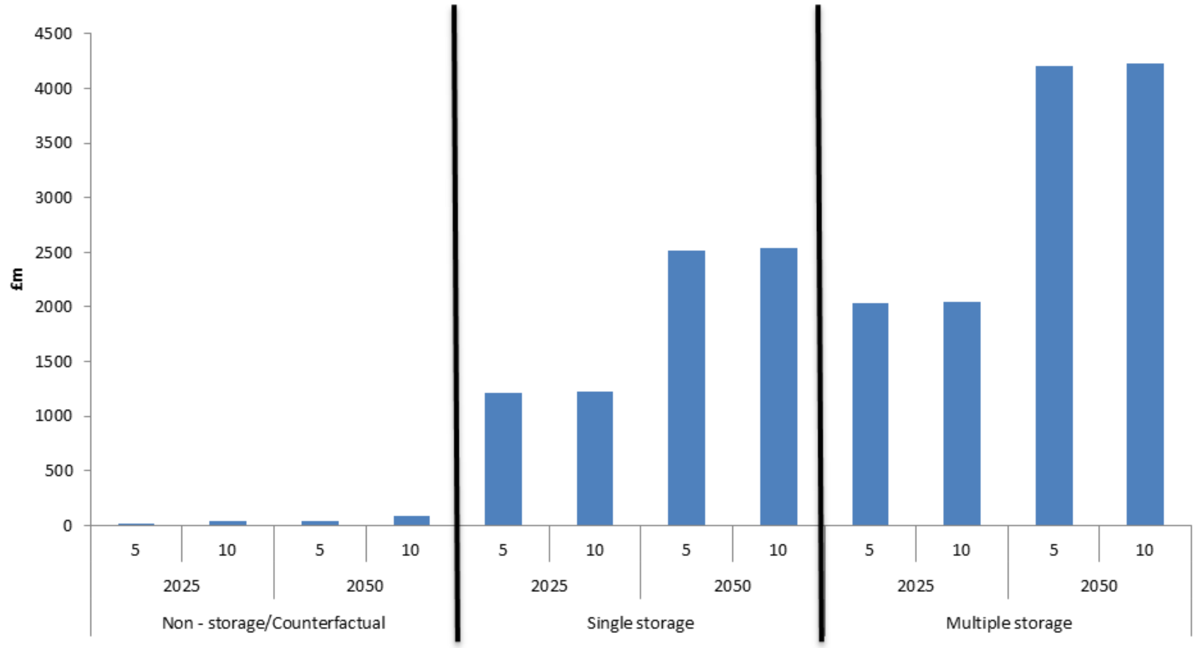


Figure 6-3 First costs

Key findings:

- First costs are higher at later installation dates due to the indexation applied in the tool (see Section 3.2.5).
- NPVs are lower for later installation dates. This is partly due to the effects of discounting and partly due to the 40-year life cycle applied to the pipework Assemblies, which means that in the 2050 variation the major refurbishment cycle is beyond the end of the assessment period.
- In general, the costs (both NPV and first costs) of including storage (Salt Cavern) at the H_2 transmission level is much higher than the counterfactual (non-storage). This is due to the high cost of Salt Cavern storage in the current market.
- The costs of a large single salt cavern storage is lower (about 40% lower) than multiple storage type with almost the same overall capacity (460m m^3 and 480 m m^3).

6.2.1 Analysis: Assemblies

As previously stated, three Assemblies have been used for this task (innovation): the distribution 20" LTS, Salt Cavern storage and 32" NTS. However, the counterfactual consists of a single assembly 32" NTS.

Key findings:

- For the innovation (all variants), the Salt Cavern storage represents the highest share of costs (% of the NPV total) at approximately 97-99%. This is due to the relatively short pipe distances considered (5, 10km) compared with the cost of the storage. Typically the operating pressure for the Salt Cavern storage is between 45-270bar.

- The reminder 1-3% is split in the 20" LTS and 32" NTS Assemblies, the former being the higher contribution of the two. This is due to the longer distances applied for the 20" LTS (4km, 9km) versus the 32" NTS (1km).
- The relative share of each Assembly's costs remain the same in 2025 and 2050.

6.2.2 Analysis: Normalised costs

Table 6-3 gives normalised costs for each variation. These results are presented in Figure 6-4.

Table 6-3 Normalised costs – NPV/mcm and NPV/km

Type / Storage	Date	Distance (km)	NPV total per mcm	NPV total per km
Single storage	2025	5	3.3	321.1
Single storage	2050	5	2.1	198.4
Single storage	2025	10	3.4	162.3
Single storage	2050	10	2.1	100.3
Multiple storage	2025	5	5.9	539.1
Multiple storage	2050	5	3.6	331.6
Multiple storage	2025	10	5.9	271.3
Multiple storage	2050	10	3.6	166.9
Non - storage/Counterfactual	2025	5	N/A	5.4
Non - storage/Counterfactual	2025	10	N/A	5.4
Non - storage/Counterfactual	2050	5	N/A	3.2
Non - storage/Counterfactual	2050	10	N/A	3.2

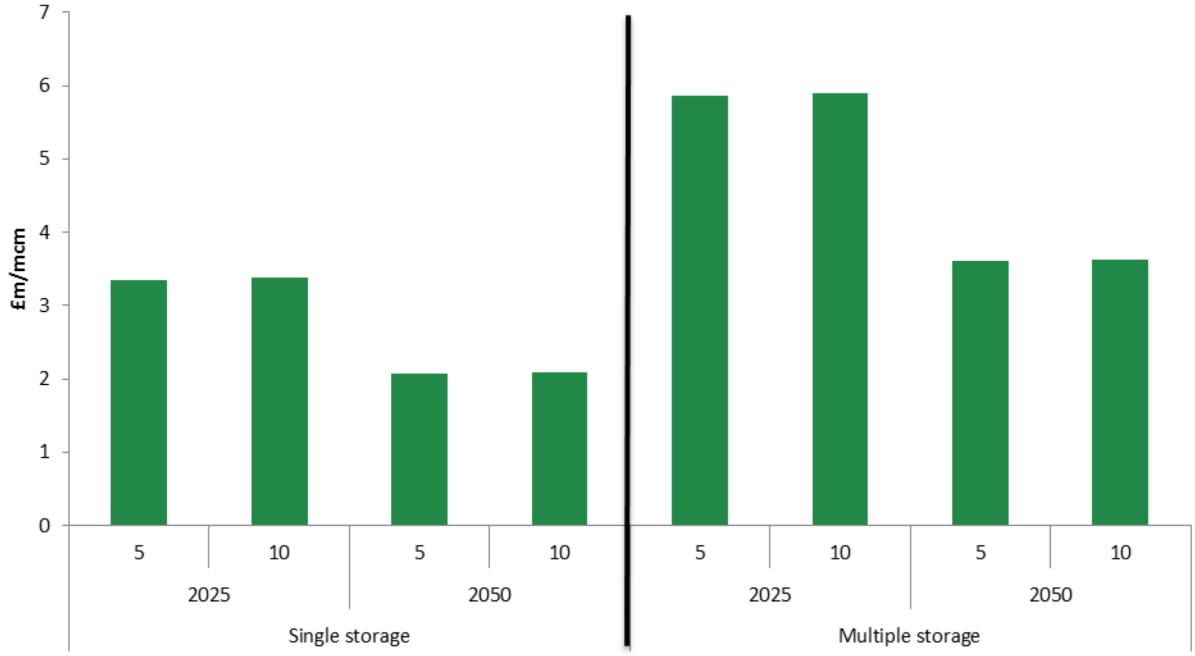


Figure 6-4 NPV total costs per mcm

Key findings:

- NPV total per mcm (million cubic metres) increases with the multiple storage variants. This is due to the higher overall costs of the multiple storage option.
- The cost per mcm is similar for 5 and 10km as the contribution of the pipeline Assemblies (LTS and NTS) are low in comparison with the cost of the storage assembly which dominates.

6.3 Limitations and further work

The limitations highlighted in the Detail Scoping also have an impact on the accuracy of the cost analysis. Specifically:

- The cost analysis does not include losses which would impact on lifecycle costs. However, losses would be minimal in new build infrastructure.
- The H_2 produced is assumed to be at the required pressure.
- The counterfactual has no storage capacity which limits its value as a comparator with the two Salt Cavern storage options (single and multiple). The main benefit of the storage options is the storage itself and not the first cost savings associated with it. There may be other cost savings related to the better performance and greater flexibility of the H_2 power generation plant versus costs of alternative storage facilities.
- Land take required for the two storage capacities has been assumed as a linear proportion.

As noted in Section 3.4, there are a number of considerations to be taken into account in relation to the design and modelling assumptions contained in first version of the ICC. In particular, cost trends and the treatment of Opex and lifecycle costs are to be revised in the second version of the tool which could impact on these results.

7 H2-I-24 Hydrogen transmission network – impact of pipeline material change

7.1 Research question overview and scope

This analysis is intended to provide a cost analysis on transmission hydrogen network including pipeline material change to avoid potential H_2 embrittlement issues. The application is considered in a rural context for power generation purposes.

The schematic Figure 7-1 shows the boundary and network layout of this project. In the context of the ICC, the Assemblies used to build the network are:

- Transmission: NTS: Buried: 32'' Hydrogen Stainless Steel 316L Pipe – 29,000,000 m^3/day.
- Transmission: NTS: Buried: 32" Hydrogen Pipe – 29,000,000 m^3/day .

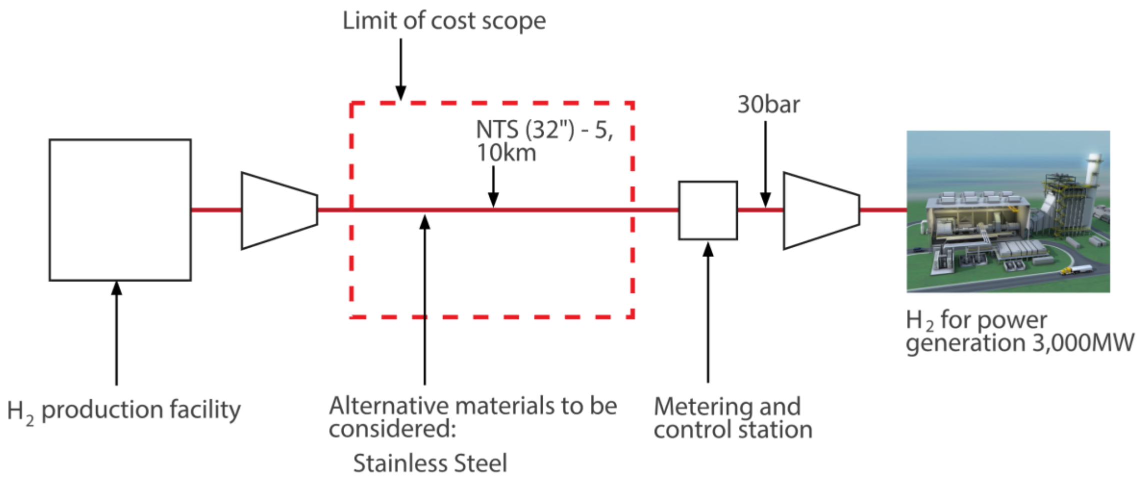


Figure 7-1 Network schematic indicating scope boundary

Table 7-1 gives the variations of installation date, materials, pipe length and context to be applied to each project.

Table 7-1 Project variants

Innovation: Stainless Steel type 316L		
Parameter	**Variants**	**Application**
Installation date	2025 2050	Each date to be applied to each of the other variants
Capacity / pipe diameter	NTS – 32”	Single capacity
Materials proposed	Stainless Steel type 316 L	Each materials to be applied to each of the other variants
Context	Rural	Single context
Length	5, 10km	Each length to be applied to each of the other variants
Mode	New build	All costs to be new build

Counterfactual: Steel grade X-42					
Description	**Application**	**Mode**	**Quantity**	**Unit**	**Date**
Transmission: NTS: Buried: 32” Hydrogen Pipe [29,000,000m^3/day]	To be used with different quantities for different variants as indicated	New build	5, 10	km	2025 2050

During the detailed scoping stage research was undertaken to determine the ‘innovation’ materials to be used in this analysis. Stainless Steel 316L was selected in part due to availability of cost data and in part due to the other benefits it has such as maintaining high purity levels of H_2 and minimising risks of H_2 embrittlement. Other materials such as polymers were considered but were not developed further due to low market penetration and the relative immaturity of the technology.

7.2 Results and analysis

Based on the variants in Table 7-1, 8 cost data sets were generated using the ICC. Each data set is representative of a different variation. The project cost parameters have remained unchanged in each variation.

NPV and first costs have been calculated as shown in Table 7-2. These results are presented in Figure 7-2 and Figure 7-3. As discussed in Section 3.3.2, first costs (undiscounted) include new build costs plus preliminary costs, contractors costs, PM engineering, land costs and contingencies but exclude any lifecycle replacement costs; NPV Capex represents the installation costs plus all lifecycle costs (which include all replacement cycles and abandonment costs - Repex – to the extent that these occur before the project end); and NPV Opex takes into account operational costs over the life of the project.

Table 7-2 Base output data

Description	Material	Date	Length (km)	First Cost (£m)	NPV Capex (£m)	NPV Opex (£m)	NPV Total (£m)
Innovation	Stainless Steel type 316L	2025	5	28.8	35.8	5.5	41.2
	Stainless Steel type 316L	2025	10	56.3	68.4	10.7	79.1
	Stainless Steel type 316L	2050	5	61.5	22.2	2.4	24.6
	Stainless Steel type 316L	2050	10	120.1	43.4	4.6	48.0
Counterfactual	Steel grade X-42	2025	5	19.3	23.2	3.6	26.8
	Steel grade X-42	2025	10	38.7	46.4	7.1	53.6
	Steel grade X-42	2050	5	40.0	14.6	1.5	16.1
	Steel grade X-42	2050	10	80.1	29.2	3.1	32.2

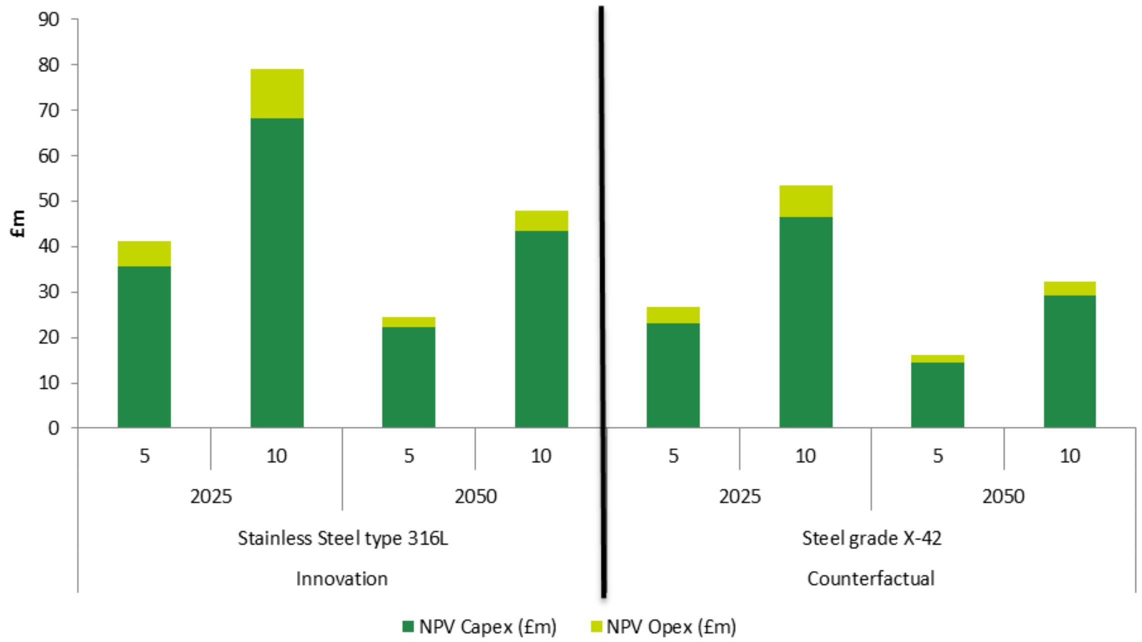


Figure 7-2 NPV Capex and Opex

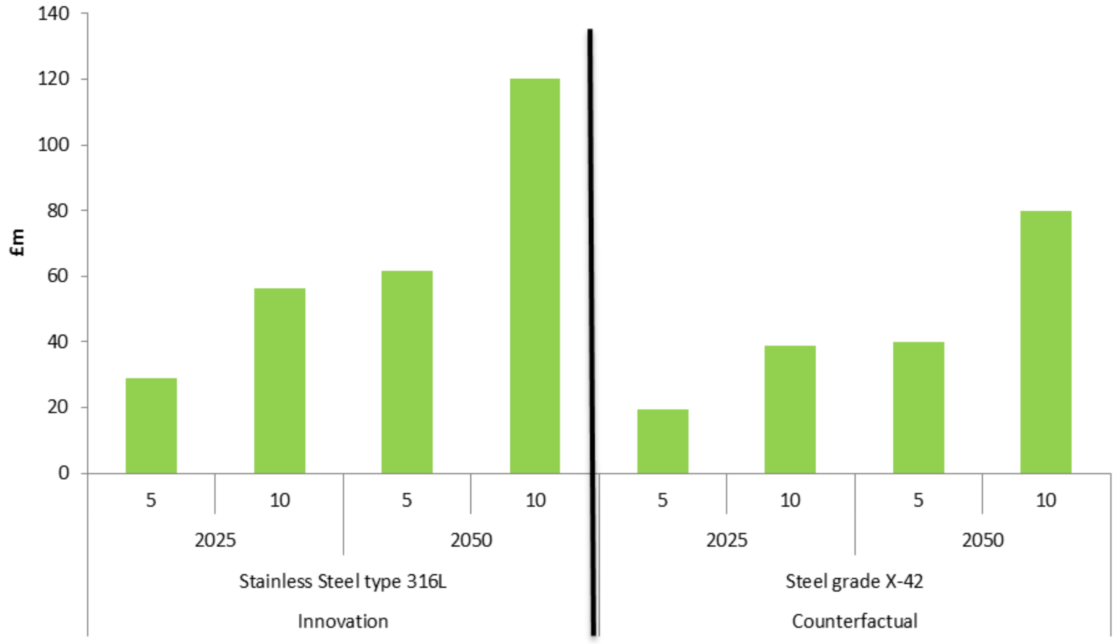


Figure 7-3 First costs

Key findings:

- Overall NPV costs are higher in 2025 than 2050 due to the effect of discounting.
- As expected, first costs are higher in 2050 than 2025 as the costs in later years are subject to indexation
- In general, the costs (both NPV and first costs) for innovation are higher than the counterfactual, by approximately 32-36%. This is due to the higher cost of the material used for the innovation variation against the counterfactual.
- As expected, the longer the pipe length the higher the project cost. See normalised cost analysis for more information.

7.2.1 Analysis: Assemblies

This task consists of a single assembly, therefore the assembly contribution analysis is not required.

7.2.2 Analysis: Normalised costs

Table 7-3 gives normalised costs for each variation. These results are presented in Figure 7-4.

Table 7-3 Normalised cost output date – first cost/km and NPV/km

Description	Material	Date	Length (km)	First Cost per km (£m)	NPV total per km (£m/km)
Innovation	Stainless Steel type 316L	2025	5	5.77	8.2
	Stainless Steel type 316L	2025	10	5.63	7.9
	Stainless Steel type 316L	2050	5	12.31	4.9
	Stainless Steel type 316L	2050	10	12.01	4.8
Counterfactual	Steel grade X-42	2025	5	3.87	5.4
	Steel grade X-42	2025	10	3.87	5.4
	Steel grade X-42	2050	5	8.01	3.2
	Steel grade X-42	2050	10	8.01	3.2

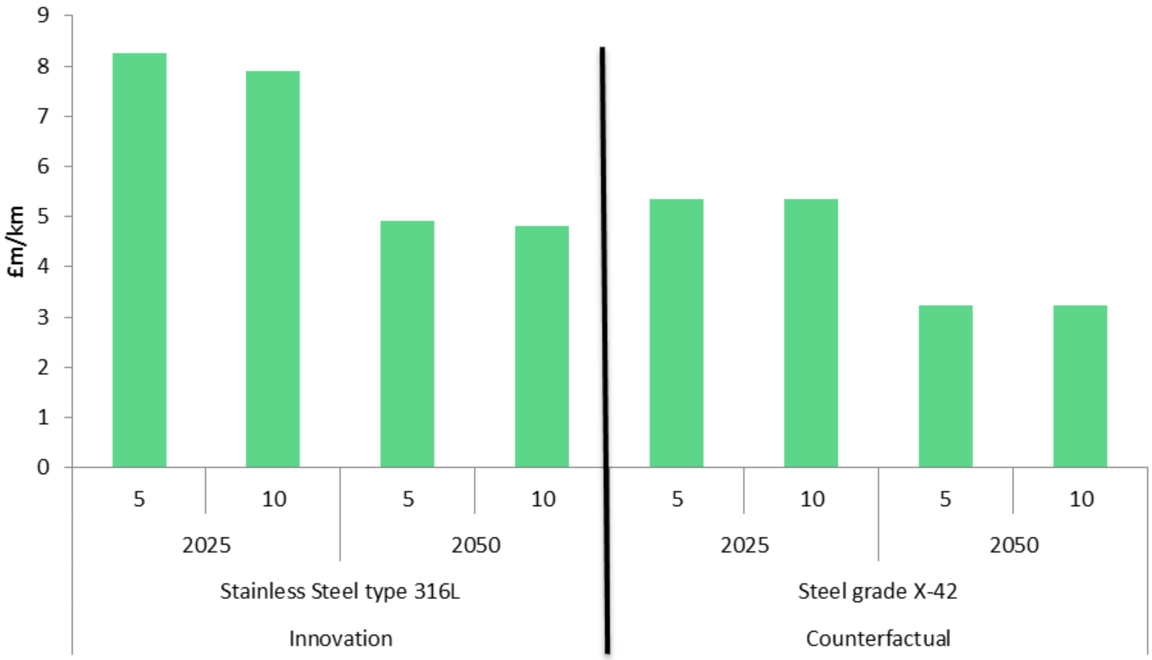


Figure 7-4 NPV total costs per km

Key findings:

- NPV total per km is significantly higher for the innovation variation – approximately 32-36% more expensive in line with the previous analysis (same pipe lengths for innovation and counterfactual have been considered).
- The cost per km decreases with the pipe length for the innovation variants (2-3% reduction). It remains constant for the counterfactual; this is likely to be associated with assumptions around the impact of scale on component costs. See further work.
- Overall NPV costs are higher in 2025 than 2050. See result and analysis section for more details.

7.3 Limitations and further work

The limitations highlighted in the Detail Scoping also have an impact on the accuracy of the cost analysis. Specifically:

- The cost analysis does not include losses which would impact on lifecycle costs. However, losses would be minimal in new build infrastructure.

Further work would include more in depth review of cost data to better understand and justify some anomalies.

As noted in Section 3.4, there are a number of considerations to be taken into account in relation to the design and modelling assumptions contained in first version of the ICC. In particular, cost trends and the treatment of Opex and lifecycle costs are to be revised in the second version of the tool which could impact on these results.

8 H2–I–25 Hydrogen Purification System at Distribution

8.1 Research question overview and scope

This analysis was intended to better understand the cost impact of incorporating a hydrogen purification system in transport refuelling sites at distribution level in rural, semi-urban, urban and London areas. An outline of the scope of the task is provided below, however it was not possible to undertake any cost analysis as cost data was not available from the market.

The schematic below shows the boundary and network layout of this project. This schematic was used to develop the BoQ that was to be used for costing purposes. In the context of the ICC, the Assemblies included in the networks are:

- Distribution: LP: Buried: 12" Rural Hydrogen Pipe - 5,800 m^3/day
- Distribution: LP: Buried: 12" Urban Hydrogen Pipe - 23,000 m^3/day
- Distribution: MP: Buried: 6" Rural Hydrogen Pipe - 87,000 m^3/day
- Distribution: MP: Buried: 6" Urban Hydrogen Pipe - 348,000 m^3/day
- Purification facility
- Compressor up to 900bars + Storage

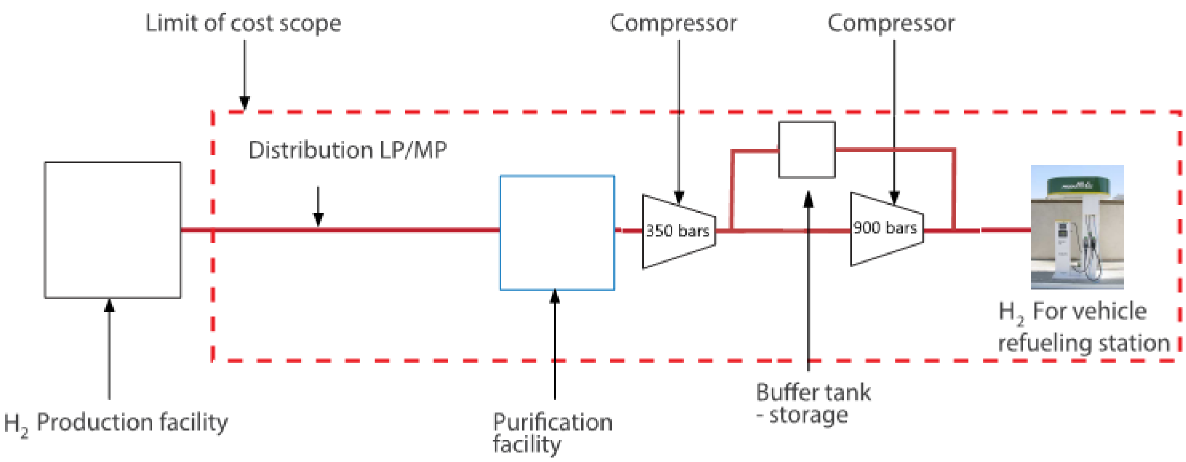


Figure 8—1 Network schematic indicating scope boundary

**Note: the refuelling station will be included in the scope according with the final product available in the market.*

Table 8-1 shows the variations of capacity, length, context, etc. to be applied to this project. In order to assess the impact of the innovation, the outputs were to be compared with a counterfactual based on the representative distribution model developed for task H2-G-22.

Table 8-1 Variations to be costed

Innovation		
Parameter	**Variants**	**Application**
Installation date	2025 2050	Each date to be applied to each of the other variants
Capacity	42,500 Nm^3/day 85,000 / 170,000 Nm^3/day (single capacity for the simulation) 340,000 Nm^3/day	Each capacity to be applied to each of the other variants
Context (and length)	Rural, semi-urban: 30 km Urban: 10km London: 1km	Each context / length to be applied to each of the other variants
Mode	New build	All costs to be new build

Counterfactual (from H-G-22)			
Description	**Application**	**Quantity**	**Unit**
Distribution: LP: Buried: 12" Rural Hydrogen Pipe [5,800 m^3/day]	Rural	30	Km
Distribution: LP: Buried: 12" Urban Hydrogen Pipe [23,000 m^3/day]	Semi-urban, urban, London areas	1, 10	Km
Distribution: MP: Buried: 6" Rural Hydrogen Pipe [87,000 m^3/day]	Rural	30	Km
Distribution: MP: Buried: 6" Urban Hydrogen Pipe [348,000 m^3/day]	Semi-urban, urban, London areas	1, 10	Km
Compressor up to 900bars + storage	Rural, semi-urban, urban, London areas	1	Nr

8.2 Results

The cost analysis for this task was not undertaken as no cost data was available from the market.

9 Summary

9.1 Key results

Some findings are the same across all projects. These include:

- First costs are higher at later installation dates. This is due to the impact of the cost trends in the ICC which inflate labour, material and plant costs over time (see Section 3.2.5). There are clearly alternative views on cost trajectories and these will influence the relative impact of deferring installation.
- NPV (Capex plus Opex) is lower for projects installed at a later date. Two factors come into play here: one, as expected, is the impact of discounting; the other is the way in which lifecycle costs are modelled in the ICC and the fact that the analysis has been undertaken for a fixed period of 60 years (2015 to 2075) irrespective of the installation date. Lifecycle costs include for a major refurbishment (100% of new build costs) at a fixed period after first instalment. For later installation dates, this major refurbishment may be beyond the analysis period and therefore not be included in the NPV calculation.
- Opex costs represent a relatively small proportion of whole life costs. It should be noted that the modelling of Opex is to be revised in the next version of the ICC which may influence the outturn values. Note also that Opex does not include the cost of losses.

A summary of findings specific to each project is given in Table 9-1.

Table 9-1 Key findings for hydrogen network research projects

Ref	Research question	Key findings
GENERIC NETWORKS		
H2-G-21	Representative hydrogen transmission model: transmission pipeline of different lengths required to transport hydrogen from production facilities to a) power generation sites and b) vehicle refuelling sites	• Pipe lengths (NTS 32") modelled for connection to production sites were 5km and 10km without the need for a compression station; pipe lengths (LTS 16") for connection to refuelling sites were modelled at longer distances up to 200km, with a compression station required for anything over 100km • NPV/km for connecting to power stations was £5.4m for installation in 2025 • NPV/km for connections to refuelling sites was in the range £3.0m to £3.5m depending on network length with the higher cost relating to the need to add in a compression station • The additional cost of the power station scenario was due to the need to larger diameter and hence more expensive pipes
H2-G-22	Representative hydrogen distribution model: distribution pipelines (LP/MP) required to connect production facilities to vehicle refuelling stations at different capacities and contexts	• Context is a strong influencer of costs, with first costs per km increasing from rural through to urban and London. This is due to the higher costs of installing pipework in more congested areas. • Pipe costs dominate the overall network cost, particularly for the longer network lengths. • There is a small increase in cost per km for the higher capacity scenarios

Ref	Research question	Key findings
INNOVATIONS		
H2-I-23	Hydrogen transmission and the impact of including storage: NTS/LTS hydrogen pipeline with a) a single salt cavern storage site and b) multiple salt cavern storage sites	• Connecting a single large storage site into the network is considerably less expensive than connecting multiple storage sites of the same capacity (460-480m m^3) • As the pipe lengths modelled were relatively short (5-10km) the storage costs dominated the overall project cost (over 95%) • Costs per mcm are considerably higher for the multi-storage option at around £6m/mcm compared with £3.3m for the single storage option • As the counterfactual chosen has no storage its value as a comparator with the storage options is limited. The main benefit of the storage options is the storage itself and not the first cost savings associated with it. There may be other cost savings related to the better performance and greater flexibility of the H_2 power generation plant versus costs of alternative storage facilities.
H2-I-24	Hydrogen transmission network and the impact of pipeline material change: comparison of stainless steel 316L pipe with conventional steel using same pipe diameter (32" NTS)	• First costs per km are higher for the stainless steel innovation at around £5.7m/lm compared with £3.9m/km for the counterfactual (2025 costs) • There is a slight reduction in cost/km for the longer stainless steel pipe lengths (2-3% lower at 10km compared with 5km) but no reduction in cost/km for the counterfactual. This requires further examination,
H2-I-25	Hydrogen distribution network and purification system	• No cost analysis was undertaken on this task as cost information on purification systems was not available from the market.

9.2 Further work

Areas for further work relate to the scope of some tasks and to issues arising from the design of the ICC. These are discussed below.

9.2.1 Scope related issues

- Issues over risk / safety associated with transmission pipelines at different pressures was noted as an area of interest. Further more detailed work could be undertaken on this in support of the original technical scope for the ICC.
- The original costing for the hydrogen infrastructure in the ICC was undertaken in 2012/13 in relation to equivalent natural gas infrastructure (ie an uplift was applied as appropriate) – see Final Report from original study. Studies have been undertaken since then which could be used to update the hydrogen costs in a future version of the tool.
- Further investigation required over the impact of scale rate modifiers within the ICC and how they impact on different network lengths (eg H-G-21).
- The hydrogen purification task can be revisited as products mature and cost data becomes available.

9.2.2 ICC issues

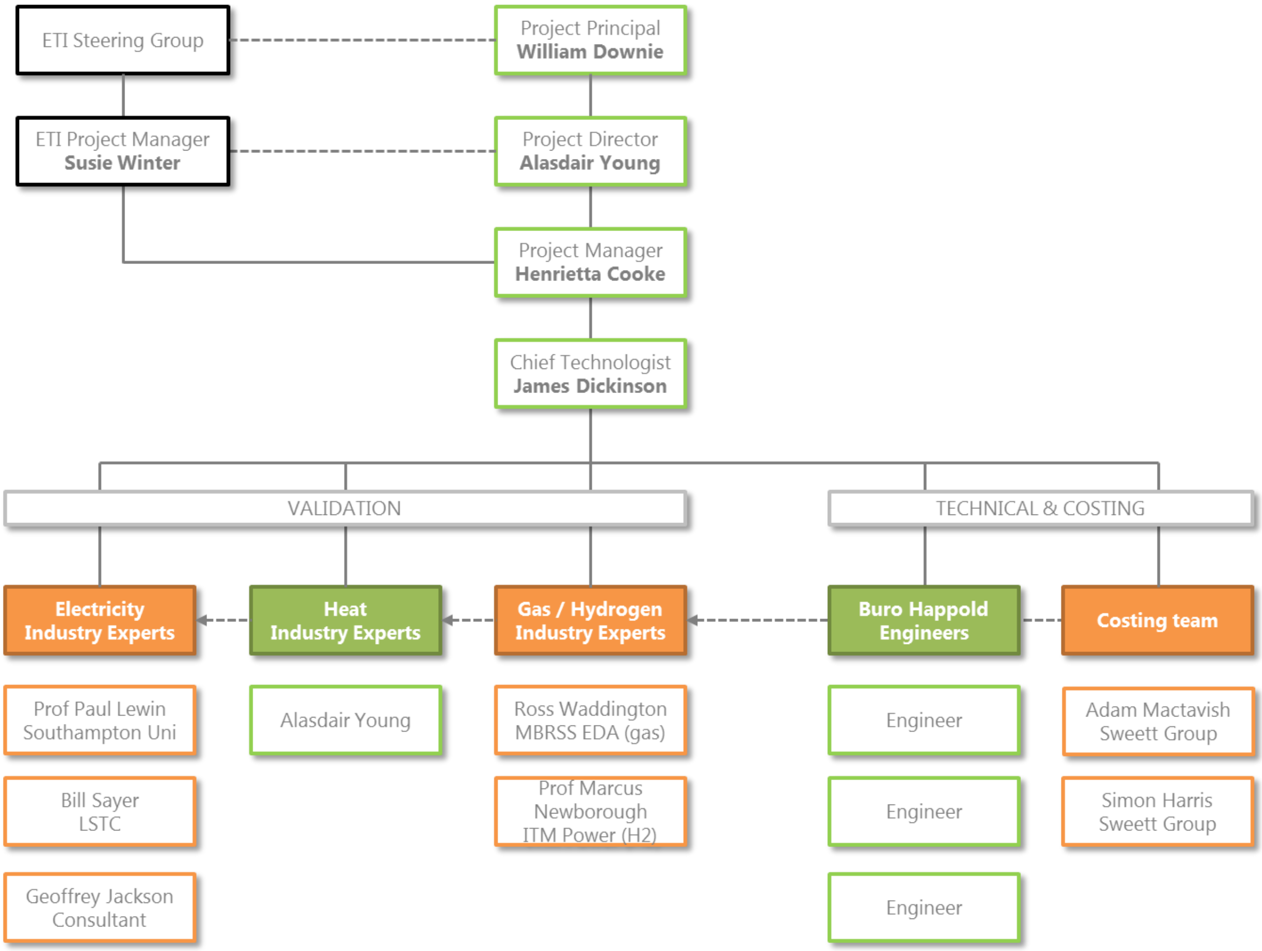
Analysis undertaken for a number of tasks raises the question as to whether the single assessment window (2015-2075) for all projects is appropriate. The primary reason this has arisen as an issue is the manner in which lifecycle costs are modelled in the ICC. As described in Section 3.2.4, lifecycle profiles are applied to each Assembly such that cash flows associated with minor and major refurbishments and with ultimate abandonment are deemed to occur in full in certain years. The effect of this is that a major refurbishment may be scheduled to occur beyond the analysis period for installations made at a later date. In the new version of the ICC, this approach is to be replaced with one that takes a more probabilistic view of replacement costs such that they are spread over the life of the asset. This approach would mitigate the effect of having a fixed analysis period.

Cost trends are being revised in the new version of the ICC.

The impact of the above suggests that further work could include re-running all tasks in the new version of the ICC. Sensitivity to cost trends could also be tested.

Appendix A Project Team

The overall project team is given in the organogram with details of the industry experts in the table below.



Role	Individual Experience & qualifications
Industry Expert – Electricity Provision of expert advice and design validation in relation to HVDC and transmission voltage HVAC cabling and power electronics	**Professor Paul Lewin, Southampton University** BSc (Hons), PhD, CEng, FIET, FIEEE Professor Lewin is Professor of Electrical Power Engineering in the School of Electronics and Computer Science, where he is also head of the Tony Davies High Voltage Laboratory. His research interests are within the generic areas of applied signal processing and control. Within high voltage engineering this includes condition monitoring of HV cables and plant, surface charge measurement, HV insulation/dielectric materials and applied signal processing. In the area of automation he is particularly interested in the practical application of repetitive control and iterative learning control algorithms. He is Vice President (Technical) of the IEEE Dielectrics and Electrical Insulation Society as well as an Associate Editor of the IEEE Transactions on Dielectrics and Electrical Insulation.
Industry Expert – Electricity Provision of expert advice and design validation in relation to AC Overhead Lines at all voltages	**Bill Sayer, LSTC Ltd** I. Eng. MIET Bill is currently a consultant with LS Transmission Consultancy Ltd where his key responsibilities are overhead line design, engineering specifications, component design/ specification, product evaluation and formulating construction procedures (wood pole and steel towers up to 400kV). Prior to working at LSTC, he was design manager for overhead lines for Balfour Beatty Utility solutions where he was responsible for the management of all engineering design issues on steel tower and wood pole overhead lines up to 400kV operation. He is Chairman BSI PEL/11 committee - Overhead Lines and UK Delegate CENELEC TC/11 WG9 – Revision to EN 50341 OHL Design > 45kV.
Industry Expert – Electricity Provision of expert advice and design validation in relation to AC Overhead Lines at all voltages	**Peter Papanastasiou, LSTC Ltd** BSc (Hons) C. Eng. MICE, FEANI (Eur Ing) Peter is a Director of LS Transmission Consultancy Ltd which has as its core business feasibility studies, topographical and ground surveys, concept and detailed design for projects for the Railway and High Voltage Electrical Power Engineering industries, in particular Overhead Lines and Substations in the power sector.
Industry Expert – Electricity Provision of expert advice and design validation in relation to electricity distribution focused on below ground electricity cabling at distribution voltages and substations.	**Geoffrey Jackson, Consultant** BSC (Hons) C. Eng Geoffrey has a long career in the electricity distribution sector from the operational level through general supervision to project management, including the installation, commissioning, safe operation, maintenance and dismantling of HV switchgear to 33kV, high and low voltage cables and cablejointing, high and low overhead lines. Other experience includes: • Project management including planning, design, tender issue and appraisal, construction and commissioning. • Extensive experience in asset condition appraisal and asset management with particular emphasis on switchgear, transformers and high voltage lines and cables.
Industry Expert – gas / hydrogen Provision of expert advice and design validation in relation to gas and hydrogen networks at all pressures.	**Ross Waddington, E Donald & Associates** Incorporated Engineer – Institute of Gas Engineers and Managers (IGEM) Ross is an Associated Director at E Donald & Associates. He is a highly experienced Senior Consultant Engineer specialising in all forms of pipeline engineering. As a Senior Manager has led multi-disciplined design teams on major Regeneration and large scale Renewable Energy projects across the UK.

Role	Individual Experience & qualifications
Industry expert – hydrogen Provision of expert advice in relation to hydrogen infrastructure	**Marcus Newborough, ITM Power** FREng CEng MSc PhD Marcus is Development Director at ITM Power where he supervises the analysis of existing and new electrolyser applications, hydrogen system design requirements for business development opportunities and demonstration projects, and the development of electrolyser products. Prior to joining ITM, he was a Research Chair at Herriot-Watt University where he led the Heriot-Watt Energy Academy as a pan-university mechanism for building partnerships in energy-related research. He established a research group which investigated pathways to a lower-carbon energy system, focusing on the assessment of demand side solutions in buildings, micro-generation, DSM and hydrogen energy systems.

Appendix B Project cost functionality

Extract from:

Energy Infrastructure 2050 Final Report, 22 November 2013, available from the ETI

Overview

The model contains a wealth of information and is provided with a number of tools and interfaces to enable users to adapt it to their needs and to extract data in ways that are both meaningful and useful. Its modular structure ensures that it is 'future proof' in that new Components and Assemblies can be added as required, either as more detailed cost data becomes available or an innovative technology becomes available. Data is also available to be extracted for use in other models or form as it is all in Excel cells which can be read by other applications or spread sheet tools.

It is anticipated that the primary use of the model will be in exploring the costs of projects and comparing options to help determine an optimal solution. In this chapter an overview of the Project functionality is provided along with some specific examples of questions the model can help in answering.

As mentioned elsewhere in this report, it must be noted that **the cost model does not allow for any form of system design.** Projects need to be designed as a separate exercise such that they can be expressed as a 'bill of quantities' (BoQ)[8] of constituent Assemblies. This 'bill of quantities' is used to model various aspects of the Projects for comparative purposes.

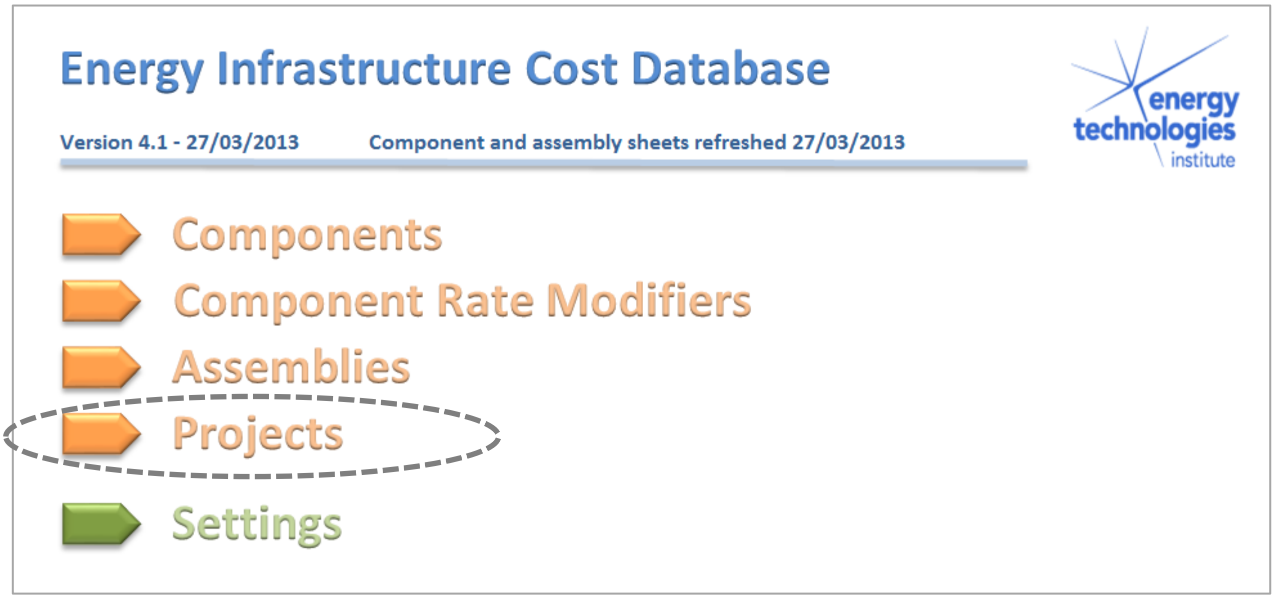


Figure B—1: Screen shot of start page of Infrastructure Cost Model

Project functionality

[8] The term 'bill of quantities' is used to refer to the data required to be input to the cost model in order to extract overall project costs. The quantity of each Assembly used to build the Project is required and this is input via the Project Data sheet of the model. This is further explained in the User Manual.

The Project functionality is a key analytical tool within the Cost Model. It enables users to cost systems of Assemblies which can be compared under different variations. In particular it allows for:

- The analysis of Projects of any scale or level of complexity from a single Assembly of a single vector to a multiple range of Assemblies across different vectors
- The creation of Projects that involve a transition over time such as the repurposing of gas to hydrogen over a 20 year period, or the inclusion of a transformative technology mid-way through the analysis period
- The modification of future cost trends so as to take into account the user's view of market factors both at a Project wide scale and individually for differing technologies as encapsulated by Components. These modifications can reflect general economic assumptions (such as labour rates / skills shortages) and technology specific assumptions such as the impacts of technology maturity and rates of deployment.

The details of how Projects are created within the model are provided in the User Manual. Key aspects of their structure and use are provided below.

Project cost calculation

Cost build up from Components and Assemblies

The calculation of Project costs uses the maximum and minimum capital cost of all Components to determine upper and lower bounds of total Project cost over the Project life. Project baseline cost is determined using rate modifiers, described in Section 7.3.3 and as outlined schematically in Figure 8—2, applying a simplified triangular Monte Carlo simulation model using the maximum, minimum and most likely cost values and allowing the user to interrogate cost probabilities based on Component cost variability.

A Project can specify quantities of Assemblies at different operational stages, that is new build, refurbished, repurposed or abandoned, each to be added at a specific period. Costs of each operational stage are built up for each Assembly and then for the Project as a whole based on:

- Capital costs
- Lifecycle costs
- Operating costs

The build-up of each of these cost profiles at the Component and Assembly level is described in Chapter 7. The user has the option to define each of the rate modifiers at the Project level or for individual Assemblies. The Project contains cost profile information for each Assembly covering each year of the defined lifecycle period.

Operating costs over this period will vary as the asset ages in line with the operating cost profile assigned to the Assembly and the major and minor replacements scheduled in the assembly lifecycle plan. For new build Assemblies there is no existing asset to be replaced, repurposed or abandoned, however for other Assembly options the operating costs presented are the net cost after an existing Assembly has been removed. The impact of this is the removal of the annual operating costs associated with the existing Assembly that is being refurbished, repurposed or abandoned.

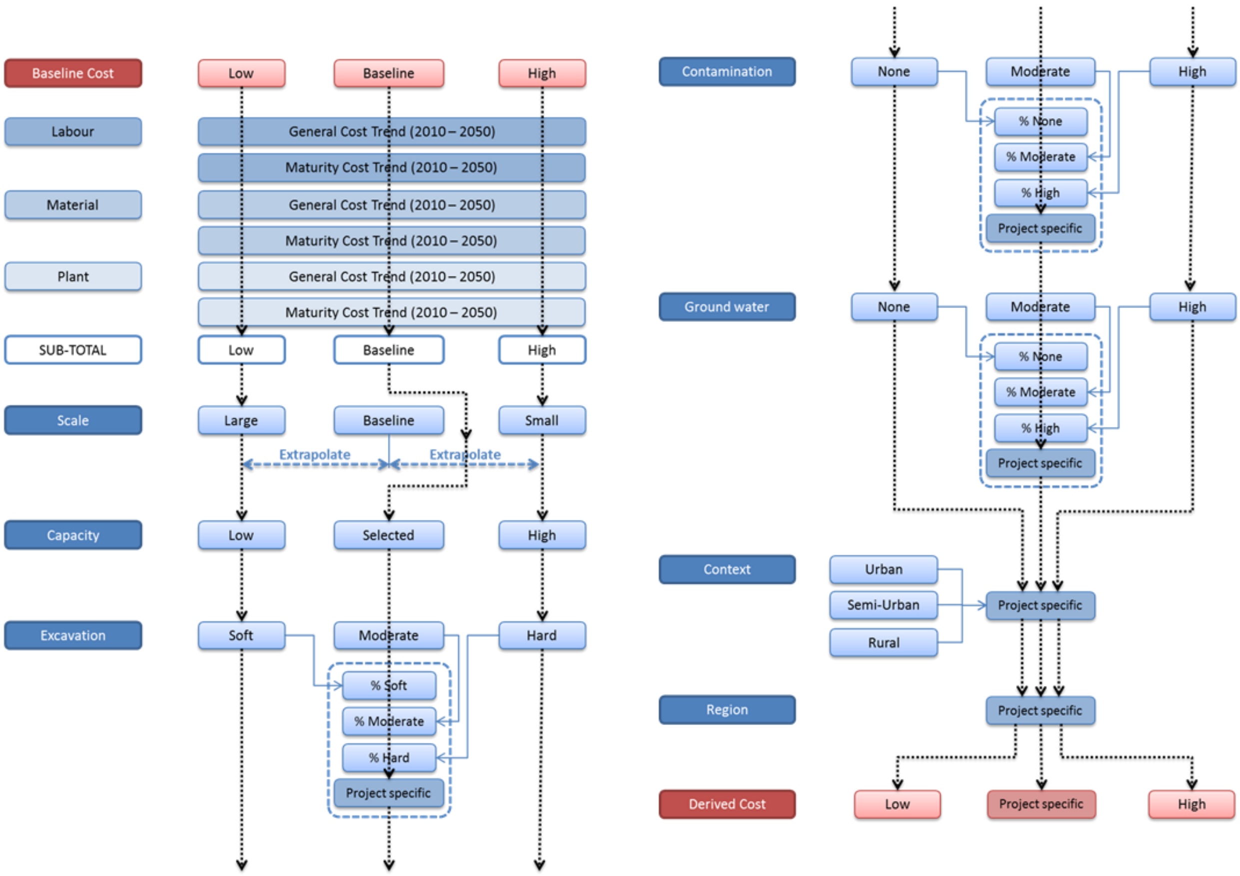


Figure B—2: schematic to illustrate application of Rate Modifiers to Projects

Project Level costs and adjustments

There are a number of costs that are applied directly at Project level. These include project management, preliminaries, contractor overheads and profit, and contingencies. These are added as a percentage mark-up applied to the capital and lifecycle costs incurred in each year of the project once the project Assembly costs have been calculated.

It is also possible to modify costs specifically for the Project. Key adjustments include:

- Cost trends: labour / materials / plant. For each a high, baseline or low rate increase can be selected.
- Ground conditions: excavation difficulty, ground contamination and ground water. For each factor, a percentage can be specified to reflect the proportion of ground conditions expected to be encountered on the Project.

- Optimism bias: There is a demonstrated, systematic, tendency for project appraisers to be overly optimistic. The HM Treasury Green Book[9] advises that, to address this tendency, "appraisers should make explicit, empirically based adjustments to the estimates of a project's costs, benefits, and duration". The Infrastructure Cost Model includes the facility for users to apply Optimism bias factors following HM Treasury Green Book guidance. The model includes a default upper and lower bound however this can be adjusted by the user if required.

Project Dashboard

The Project Dashboard presents total Project costs over the specified project life by vector and by cost type (capital and operational) (Figure 8—3) and displays these graphically as a cumulative cash flow (Figure 8—4).

A breakdown of the top five Assemblies and Components in terms of their percentage of total cost is provided to give a view on which aspects of the Project might be deemed critical and potential targets for innovation.

A Net Present Value (NPV) calculation is also calculated. NPV is a useful tool to provide comparative costs to enable comparison of two different projects bringing them back to the same year. Effectively this provides a discounted life cycle cost and will always be negative as there are no revenues. The discount rate set in the model is 3.5% however this can be changed by the user as required (Figure 8—3).

[9] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

PROJECT DASHBOARD

Ref	20130801 1313
Description	Electricity transmission - East Midlands - test
Owner	HC

Region	East Midlands Region
Context	Rural
Scale	Baseline
Labour cost	Baseline
Materials cost	Baseline
Plant cost	Baseline

PROJECT COSTS IN 2015	P80	P50	P10
Totals	6,980,531,817	5,806,365,013	2,796,428,255
Electricity	4,689,367,012	3,900,692,082	1,879,007,562
Natural gas	-	-	-
Hydrogen	-	-	-
Heat	-	-	-
Preliminaries	702,104,635	584,067,594	281,516,961
Contractors Overheads	269,140,110	223,892,578	107,914,835
Contingencies	565,194,231	470,174,413	226,621,154
PM, Engineering, etc.	746,056,385	620,630,226	299,139,923
Land Costs	8,669,443	6,908,121	2,227,819

TOP 5 ASSEMBLIES

Assembly	% TOTAL
Transmission: HVAC: Overhead: 400kV line [6380 MVA] (New Build)	53.4%
Conversion: HVAC: None: 400kV to 132kV Conversion [670 MVA] (New Build)	36.9%
Transmission: HVAC: Overhead: 275kV line [2600 MVA] (New Build)	7.5%
Conversion: HVAC: None: 275kV to 132kV Conversion [720 MVA] (New Build)	2.2%
#N/A	#N/A

TOP 5 COMPONENTS

Component	% TOTAL
AA12 - Electricity - Overhead - Conductors - Refurb, Repurpose and Abandon: Refurbish 400kV HVAC overhead transmission line	28.0%
AD12 - Electricity - Conversions - On-shore - Refurb, Repurpose and Abandon: Refurbish 400kV to 132kV conversion (two circuits)	27.9%
AA11 - Electricity - Overhead - Conductors - New: 400kV HVAC Overhead transmission line	25.4%
AD11 - Electricity - Conversions - On-shore - New: 400kV to 132kV conversion (two circuits)	9.0%
AA11 - Electricity - Overhead - Conductors - New: 275kV HVAC Overhead transmission line	4.0%

OPEX COSTS DURING PERIOD 2015 - 2074	P80	P50	P10
Totals	3,874,621,240	2,910,646,056	1,812,783,642
Electricity	3,874,621,240	2,910,646,056	1,812,783,642
Natural gas	-	-	-
Hydrogen	-	-	-
Heat	-	-	-

NET PRESENT VALUE AT 2015	Project NPV	Optimism Bias Adjusted (Go there)	
		Lower	Upper
Totals	3,934,378,815	4,170,441,544	6,531,068,832
CAPITAL COSTS IN 2015			
Electricity	2,216,274,185	2,349,250,636	3,679,015,146
Natural gas	-	-	-
Hydrogen	-	-	-
Heat	-	-	-
Preliminaries	331,826,529	351,736,121	550,832,038
Contractors Overheads	127,200,169	134,832,180	211,152,281
Contingencies	267,120,356	283,147,577	443,419,790
PM, Engineering, etc.	352,598,870	373,754,802	585,314,123
Land Costs	7,284,500	7,721,570	12,092,270
OPEX DURING PERIOD 2015 - 2074			
Electricity	632,074,207	669,998,659	1,049,243,183
Natural gas	-	-	-
Hydrogen	-	-	-
Heat	-	-	-

Figure B—3: Screen shot of Project Dashboard - top section

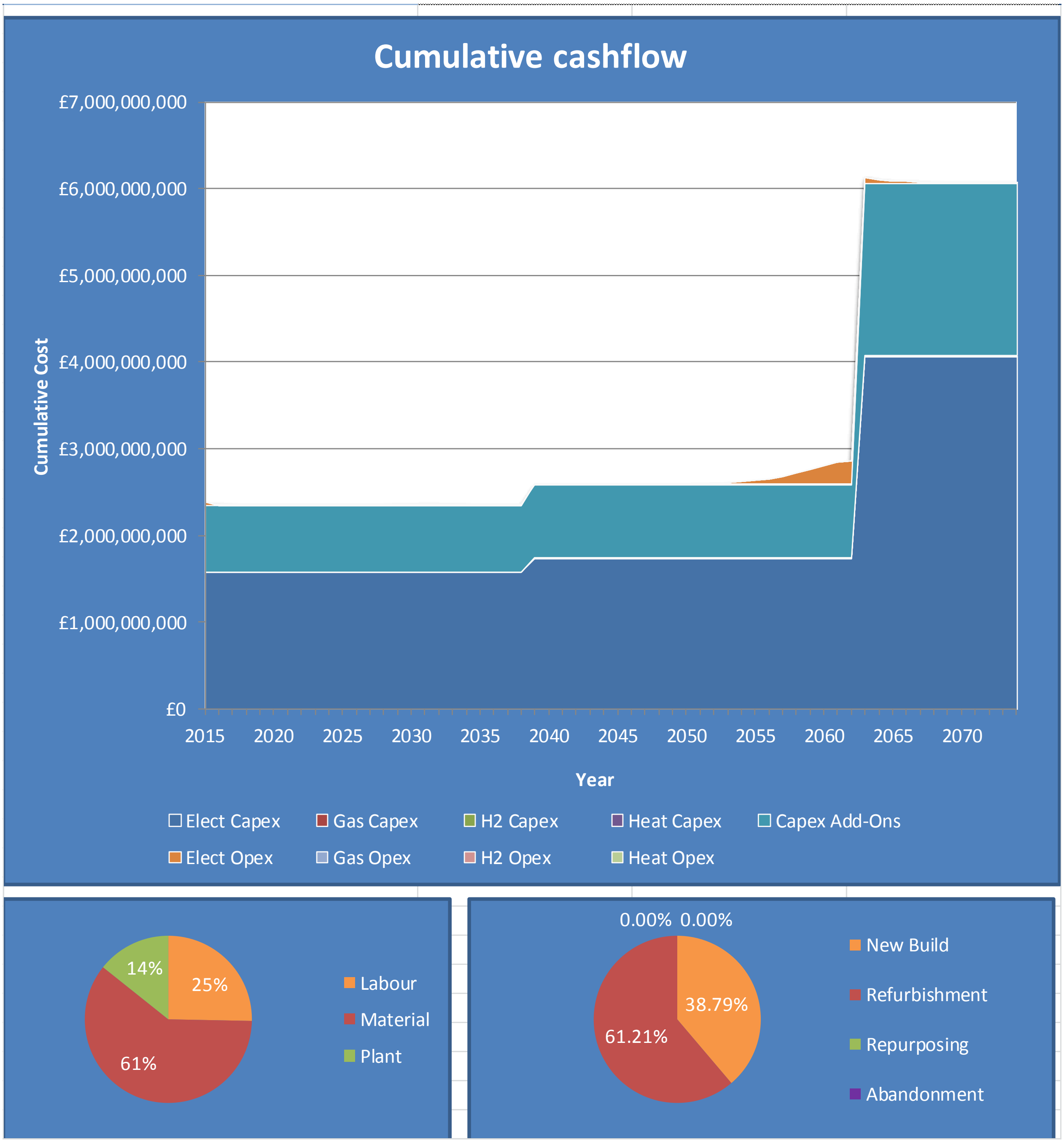


Figure B—4: Screen shot of Project Dashboard - bottom section

Examples of uses

There are a number of ways in which the model can support analysis and decision making in respect of energy projects and strategy. Table 8-1 outlines a variety of potential variations along with an explanation of how the cost model can be used. Limitations in each case are also discussed. Note that for all these, the data can be exported directly from the model (capital and operational costs on an annual basis) for analysis in other models and tools.

Table B—9-2 Examples of variations which could be informed by the model

	Variation / objective	Model capability	Limitations / factors to consider
1	To compare the cost of implementing a new hydrogen system vs repurposing of existing gas system over any period up to 2050	Two separate Projects need to be input by the user developed based on a 'bill of quantities' for each system. The detail attached to each BoQ should include the dates of the addition or repurposing, and provide any relevant context regarding locality, ground conditions etc. The user can adjust cost rate modifiers as required to match system design assumptions and views of cost trends for each vector. The model will provide cost out turns for each Project which can be compared.	Given that the system is designed outside the model, the results should be straightforward to achieve. There could be issues over the availability of all Assemblies included in the relevant system designs. Either the 'next best' can be selected or new Components and Assemblies can be added. The model will not give any information on relative system efficiency as this is provided separately in the Technical Scoping Tables (see Section 3.3.2).
2	To compare the cost of implementing a new electrical network to support a certain level of demand vs a gas network or heat network to support the same demand	As above, separate Projects can be input to the model based on appropriate BoQs for the system design for each vector.	As above, the results should be straightforward to achieve. Note that the Project functionality does not allow for capital costing only and is set up to provide whole life costs for the specified project period. However data can be readily extracted for analysis elsewhere.
3	To compare the ratio of Opex vs Capex for an electrical network, a gas network and a hydrogen network for supporting a certain level of demand for a particular region within the UK	As above, separate Projects can be input to the model based on appropriate BoQs for the system design for each vector. Opex and Capex are presented separately on the Project dashboard and can be extracted for analysis elsewhere.	The relevant ratio would have to be calculated outside the model. The model will not give any information on relative system efficiency as this is provided separately in the Technical Scoping Tables (see Section 3.3.2).
4	To explore the transitional cost differences of developing an electrical network over a period of 30 years based on small capacity increments vs large scale deployment at strategic intervals	The model allows for input of different Assemblies at different time periods over any period up to 150 years. Thus it can accommodate alternative assumptions regarding the time and scale of deployment. Again, it relies upon the development of suitable BoQs and the relevant time of their deployment. In this case, two separate Projects would be input by the user and the two sets of results compared.	Given that the system is designed outside the model, the results should be straightforward to achieve. There could be issues over the availability of all Assemblies included in the relevant system designs. Either the 'next best' can be selected or new Components and Assemblies can be added. The model will not give any information on relative system efficiency as this is provided separately in the Technical Scoping Tables (see Section 3.3.2).

	Variation / objective	Model capability	Limitations / factors to consider
5	To examine the cost of decommissioning the UK gas network between now and 2050 and determining the optimum cost path to do this.	The user would need to input the quantities of the existing gas assets into a Project. For each Assembly, a start date before the Project start would need to be specified to reflect the age of the asset. The model will then calculate refurbishment and abandonment costs according to the life cycle profile adopted for that Assembly. A bespoke life cycle profile could be added if required.	The model cannot determine an 'optimum' cost pathway as it is not constructed as an optimisation tool in this sense. The user would have to experiment with alternative pathways and compare costs by inputting a new Project for each individually.
6	To explore how the losses of a network determine its feasibility on a regional basis in supporting certain supply and demand infrastructures – do this analysis across different vectors.	Not possible within the model as losses are provided separately as percentages of annual energy flow within the Technical Scoping Tables and would require a better understanding of network configuration and energy flows through the network. A detailed system analysis is required.	Losses are provided as percentages in the Technical Scope Tables attached to the model (see Section 3.3.2).

Pablo Romero;Henrietta Cooke
Buro Happold Limited
17 Newman Street
London
W1T 1PD
UK

T: +44 (0)207 927 9700
F: +44 (0)870 787 4145
Email: henrietta.cooke@burohappold.com