Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY)

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

Grant Agreement Number 278177

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Disclaimer

Publishable Summary

This report documents work on the development of MS Excel workbooks for the production and utilisation of hydrogen in Task 3.3 on life cycle and economic assessment in the IDEALHY Project which is supported by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) under Grant Agreement No. 278177 with funding from the European Commission.

The aims of the IDEALHY Project and the rôle of Task 3.3 within Work Package 3 on whole chain assessment are re-iterated. The assessment procedures and the basic features of specific workbooks, developed during Task 3.3.3, for calculating the primary energy inputs, greenhouse gas emissions and internal economic costs of pathways for producing and utilising hydrogen are summarised. In particular, the process chains and key technical parameters are introduced for workbooks that represent the production of hydrogen from natural gas by steam reforming and from brown coal by gasification both with and without carbon capture and storage, and from wind and solar power by electrolysis, and the utilisation of hydrogen in fuel cell cars and buses with delivery by liquid and compressed hydrogen. Default values for the main technical parameters in the workbooks are tabulated and results derived with these default values are summarised.

The necessary functionality of the workbooks is demonstrated by providing illustrative results for total primary energy inputs, total greenhouse gas emissions and total internal costs. Results generated using default values are recorded, along with relative contributions from different parts of the relevant process chains. The effects on results of important variations in parameters and options are illustrated. These include the influence of choosing different calculation methodologies, principally in the evaluation of total greenhouse gas emissions, reflecting regulation and policy analysis. Additionally, the effects are demonstrated on results for hydrogen production from natural gas via steam reforming by including or excluding carbon capture and storage, and varying transmission pipeline and liquefied natural gas transportation distances; for hydrogen production from brown coal via gasification by including or excluding carbon capture and storage, and varying the shipping round trip distance for transporting coal; for hydrogen production from wind power via electrolysis by including or excluding salt cavern storage, and varying the load factor of wind turbines; and for hydrogen production from solar power via electrolysis by varying insolation.

The importance of these hydrogen production and utilisation workbooks is emphasised in terms of their use in conjunction with future workbooks for advanced hydrogen liquefaction, developed later during Task 3.3.4 of the IDEALHY Project, to enable eventual overall assessment of alternative pathways for the provision of hydrogen to fuel cell vehicles which will be undertaken in Task 3.3.5 and reported subsequently in Deliverable D3.17.

Key Words

Life cycle assessment of hydrogen production

Life cycle assessment of hydrogen utilisation

Economic assessment of hydrogen production

Economic assessment of hydrogen utilisation

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1. Introduction

1.1 Aims and Objectives

The aims of the IDEALHY Project, which is supported by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) under Grant Agreement No. 278177 with funding from the European Commission (EC), are:

- to reduce, substantially, the specific energy consumption of hydrogen (H_2) liquefaction,
- to optimise a generic process design for efficient H_2 liquefaction based on scaled up data, and
- to prepare a strategic plan for a prospective demonstration of efficient H_2 liquefaction at a scale of up to 200 tonnes of H_2 per day.

In addition to technical viability, these aims are being pursued within the context of whole chain assessment which includes scenario development, safety assessment, and life cycle and economic assessment, and the dissemination of results from the project.

The project is divided into six work packages (WPs) which have specific objectives:

- Within WP1, to apply a number of innovations to existing H_2 liquefaction process technologies, and to "screen" by intensive modelling of the effect of each of the innovations in combination, so as to determine the most promising options to go forward for optimisation (WP2),
- Within WP2, to take the outputs from WP1, and to carry out detailed and intensive modelling of the various plant configurations showing promise, to perform optimisation studies and to produce an optimised process for H_2 liquefaction,
- Within WP3, to carry out a whole chain assessment, including scenario development for liquid H_2 (LH_2) usage, hazard and risk assessment, and life cycle and economic assessment, to determine the impact of supplying and distributing significant volumes of LH_2 to a refuelling infrastructure,
- Within WP4, to disseminate results mainly to an expert stakeholder community, technical/scientific stakeholders and relevant decision-makers at various levels, and to provide relevant advice and manage on intellectual property rights issues,
- Within WP5, to develop a robust plan for a large-scale demonstration, at a later date, of the efficient H_2 liquefaction process, and to design a procedure and protocol for organising the demonstration, including consideration of safety issues, potential locations, "upstream" aspects, such as consideration of H_2 supplies, and "downstream "factors such as nearby markets and end-user facilities, and

- Within WP6, to provide overall management of the project in accordance with the EC contract and the Consortium Agreement.

1.2 Life Cycle and Economic Assessment

Life cycle and economic assessment is being undertaken in Task 3.3 within WP3 of the IDEALHY Project. The objectives of Task 3.3 are:

- to evaluate and compare the environmental impacts and economic costs and benefits of all relevant pathways for the supply, from selected sources, and delivery of LH_2 to fuelling stations and its subsequent use in suitable road passenger vehicles relative to current pathways based on crude oil from conventional sources, compressed gaseous H_2 and LH_2 from existing liquefaction processes.

The specific environmental impacts of this assessment are:

- primary energy inputs, chiefly in the form of energy from depletable resources, such as fossil and nuclear fuels, but extended, where necessary, to include renewable sources of energy, and

- prominent greenhouse gas (GHG) emissions consisting of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The economic costs addressed by this assessment consist of:

- internal costs, in €, which exclude taxes and financial incentives.

These assessments are performed by means of MS Excel workbooks which have a standardised structure and format to accommodate necessary functionality (for investigating the effect of key parameters) and transparency (by documenting all assumptions and sources of data). In relation to the assessment of GHG emissions, methodologies are adopted which are intended to accommodate regulation, as set out in the Renewable Energy Directive (RED) of the EC (Ref 1), and policy analysis, as reflected by the requirements of the European Reference Life Cycle Database (ELCD; previously known as the International Reference Life Cycle Data System - ILCD) of the official European Life Cycle Assessment Platform (Refs. 2 to 5), as well as the FC-HyGuide (Refs. 6 to 8).

Task 3.3 is divided into five Sub-Tasks that are composed of the following:

- Sub-Task T3.3.1: Baseline Workbook Development involving the preparation of a standard workbook that represents current transportation pathways based on the production and refining of crude oil, and the use of petrol and diesel in conventional cars and buses, providing results in the form of total primary energy consumption, total GHG emissions, and total internal economic costs per vehicle kilometre (which this report documents).

- Sub-Task T3.3.2: Liquid Hydrogen Pathway Specification involving establishment of the agreed details of specific pathways for the production of H_2, its liquefaction, tanker transport, re-gasification at the fuelling station, and its utilisation by suitable cars and buses.

- Sub-Task T3.3.3 Hydrogen Production and Utilisation Workbook Development involving the preparation of standard workbooks, based on the outcomes of Sub-Task 3.3.2, for the production of H_2 and its subsequent utilisation in fuel cell cars and buses.

- Sub-Task T3.3.4 Hydrogen Liquefaction Workbook Development involving the preparation of standard workbooks, incorporating simplified models, based on the outcomes of Task 3.3.2 and relevant results from WP2 and WP5, of chosen options for H_2 liquefaction.

- Sub-Task T3.3.5 Techno-Economic Analysis and Comparison involving preparation of a report containing illustrative results, in the form of net primary energy savings, net GHG emissions savings and relative economic costs/benefits, of H_2 production, liquefaction and utilisation pathways compared with conventional transportation pathways utilising crude oil, and transportation pathways utilising compressed H_2 and LH_2 derived from existing liquefaction processes, based on the outcomes of Sub-Tasks 3.3.1 to 3.3.4.

2. Workbooks

2.1 Assessment Procedures

The assessment procedures incorporated in the MS Excel workbooks for the IDEALHY Project have been detailed previously (Ref. 9). These reflect the main focus of the assessment which is the evaluation of total GHG emissions associated with the production and utilisation of H_2. In particular, the workbooks incorporate assessment procedures which are consistent with the EC Renewable Energy Directive (Ref. 1) for regulatory purposes and with consequential LCA for policy analysis purposes. The essential features for the EC RED methodology are:

- Exclusion of total GHG emissions associated with the construction, maintenance and decommissioning of plant, equipment, machinery and vehicles.
- Co-product allocation based on energy content.
- Where relevant (in situations where biomass is a feedstock), exclusion or inclusion of total GHG emissions associated with indirect land use change (iLUC) depending on the possible introduction of "iLUC factors" by the EC.

The essential features for policy analysis with consequential LCA are:

- Inclusion of total GHG emissions associated with the construction, maintenance and decommissioning of plant, equipment, machinery and vehicles.
- Co-product allocation based on substitution credits although this presents significant practical challenges due to the need to model the complete and global consequences of product displacement.
- Where relevant (in situations where biomass is a feedstock), inclusion of total GHG emissions associated with iLUC, if possible, although necessary global modelling is another major practical challenge with no broadly agreed approach and estimates at the moment.

Additionally, the MS Excel workbooks provide clear specification of the goal and scope of the evaluation, as required by the ELCD and the FC-HyGuide. The methodologies for calculating GHG emissions can be fairly easily extended to the evaluation of total primary energy inputs. However, estimation of internal economic costs follows financial accounting rules albeit applied in a quite unsophisticated manner for current purposes. It should be noted that the results generated by the MS Excel workbooks also depend on certain critical assumptions including the following considerations:

- Primary energy is defined as an indicator of energy resource depletion and, as such incorporates the energy contained in fossil and nuclear sources. However, it is possible to determine the energy provided by renewable sources when these are the main feedstocks for H_2 production. Currently, this has to be done by performing separate calculations based on information generated by the relevant MS Excel workbooks.

- Estimated emissions of CO_2, CH_4 and N_2O can be converted to equivalent (eq.) CO_2 by means of Global Warming Potentials (GWPs). Values of GWPs depend on the chosen time horizon under consideration. Additionally, these values are subject to revision from time-to-time by the Intergovernmental Panel on Climate Change (IPCC) as scientific understanding improves. In the context of LCA, the GWPs adopted are governed by the choice of methodology. Currently, the RED specifies GWPs of 23 kg eq. CO_2/kg CH_4 and 296 kg eq. CO_2/kg N_2O for a 100 year time horizon based on the IPCC Third Assessment Report (Ref. 10). More recent equivalent GWPs of 25 kg eq. CO_2/kg CH_4 and 298 kg eq. CO_2/kg N_2O are given in the IPCC Fourth Assessment Report (Ref. 11).

- The internal economic cost estimates generated by the MS Excel workbooks are in € for 2012. These results are intended to reflect economic evaluation across the European Union (EU). However, the limitations of this are recognised and results should only be considered as approximations. This is because, apart from inherent extrapolation across 27 Member States with different internal economic conditions, it has also been necessary to incorporate cost data from countries outside the EU and for years other than 2012. Hence, it has been necessary to apply inflation indices and exchange rates which introduce their own uncertainties.

2.2 Basic Workbook Features

Each MS Excel workbook has a standard structure, consisting of a series of worksheets, which has been described and presented previously (Ref. 9). In particular, the main elements of this structure are an Input worksheet which enables the values of specified parameters to be altered, a Unit Flow worksheet which provides a visual presentation of the process chain represented by the workbook, individual Process Stage worksheets where detailed calculations are performed, and Summary worksheets which present the results. By adopting this structure, which has been used by North Energy Associates Ltd in numerous other projects, it is possible to ensure that the workbooks accommodate necessary functionality to model the effects of variations in specified parameters and contain adequate transparency to promote confidence in the subsequent results.

3. Production and Utilisation Pathways

3.1 Pathway Specification

The main pathways for the production and utilisation of H_2 considered in the IDEALHY Project, which were established through discussion amongst relevant partners, are recorded in Deliverable D3.14 (Ref. 12). These have resulted in the development of the following MS Excel workbooks:

- IDEALHY - Natural Gas Steam Reforming v05.xlxs for the production of H_2 from natural gas by means of steam reforming,
- IDEALHY - Brown Coal Gasification v14.xlxs for the production of H_2 from brown coal by means of gasification,
- IDEALHY - Wind Power Electrolysis v13.xls for the production of H_2 from surplus electricity from offshore wind power by means of electrolysis,
- IDEALHY - Solar Power Electrolysis v09.xlxs for the production of H_2 from electricity from concentrated solar power by means of electrolysis,
- IDEALHY - Liquid Hydrogen Delivery v06.xlxs for the delivery of H_2 to refuelling stations by LH_2 tanker.
- IDEALHY - Compressed Hydrogen Delivery v06.xlxs for the delivery of H_2 to refuelling stations by compressed gaseous H_2 tanker, and
- IDEALHY - Hydrogen Utilisation v04.xlxs for use of hydrogen in fuel cell cars and buses.

The specific details of these pathways and the subsequent process chains represented in the relevant MS Excel workbooks are summarised below. For the MS Excel workbooks which address H_2 production, it should be noted that the characteristics of the H_2 available, in terms of purity and pressure, are specified accordingly.

3.2 Hydrogen Production by Steam Reformation of Natural Gas

The main features of the process chain represented in the IDEALHY Natural Gas Steam Reforming v05.xlxs workbook are summarised in Figure 1. The sources of natural gas that can be considered for evaluation are raw natural gas in onshore and offshore deposits. Once extracted and collected by pipelines to a centralised processing plant, major impurities are removed, especially CO_2 (which can either be released to atmosphere or captured for storage). After this, two means of transporting the processed natural gas to the steam reforming plant are available. One involves overland transportation by means of transmission pipelines. The other consists of liquefying the natural gas, transporting it in liquefied natural gas (LNG) ships to a receiving port where it is re-gasified and introduced into a local transmission pipeline. The delivered natural gas is converted into H_2 (with an assumed purity of 99.500% H_2) in the steam reforming plant and processed in an integrated pressure swing absorption (PSA) unit (to produce a purity of 99.99% H_2 and a pressure of 20 bars). CO_2 generated during steam reforming can either be released to atmosphere or captured and transferred by overland and/or subsea pipelines for storage in depleted oil and gas deposits. Carbon capture and storage (CCS) is accommodated within the MS Excel workbook.

The main technical parameters which can be varied in the IDEALHY Natural Gas Steam Reforming v05.xlxs workbook are summarised as follows:

- Characteristics of raw natural gas (onshore and offshore); gross and net calorific value, CH_4 content and CO_2 content,
- Features of transmission pipelines (onshore and offshore); length, capacity, load factor and life,
- Share of raw natural gas supplied by onshore and offshore sources,
- Features of natural gas processing plant; capacity, load factor, life and option for CCS,
- Features of processed natural gas transmission to steam reforming plant; length, load factor and life of pipes, and number, average power rating and life of compressors,
- Features of natural gas liquefaction plant; type of technology, capacity, load factor and life,
- Features of LNG shipping; type of technology and round trip transport distance,
- Features of LNG re-gasification plant; type of technology and losses,
- Features of re-gasified natural gas transmission to steam reforming plant; length, load factor and life of pipes, and number, average power rating and life of compressors,
- Features of steam reforming plant; capacity, availability, life and option for CCS, and
- Features of CCS system; length of pipeline (overland and subsea), CO_2 leakage rate, number of injection wells and bottom hole pressure.

A summary of key technical parameters and the default values adopted in the IDEALHY - Natural Gas Steam Reforming v05.xlxs workbook is given in Table 1. A summary of the key technical parameters and the default values adopted for the CCS system in both the IDEALHY - Natural Gas Steam Reforming v05.xlxs and IDEALHY - Brown Coal Gasification v14.xlxs workbooks is provided in Table 2. It should be noted that some of these default values are different from those assumed for CCS associated with natural gas processing.

Figure 1 Main Process Chain Features of the MS Excel Workbook for the Production of Hydrogen from Natural Gas by Means of Steam Reforming

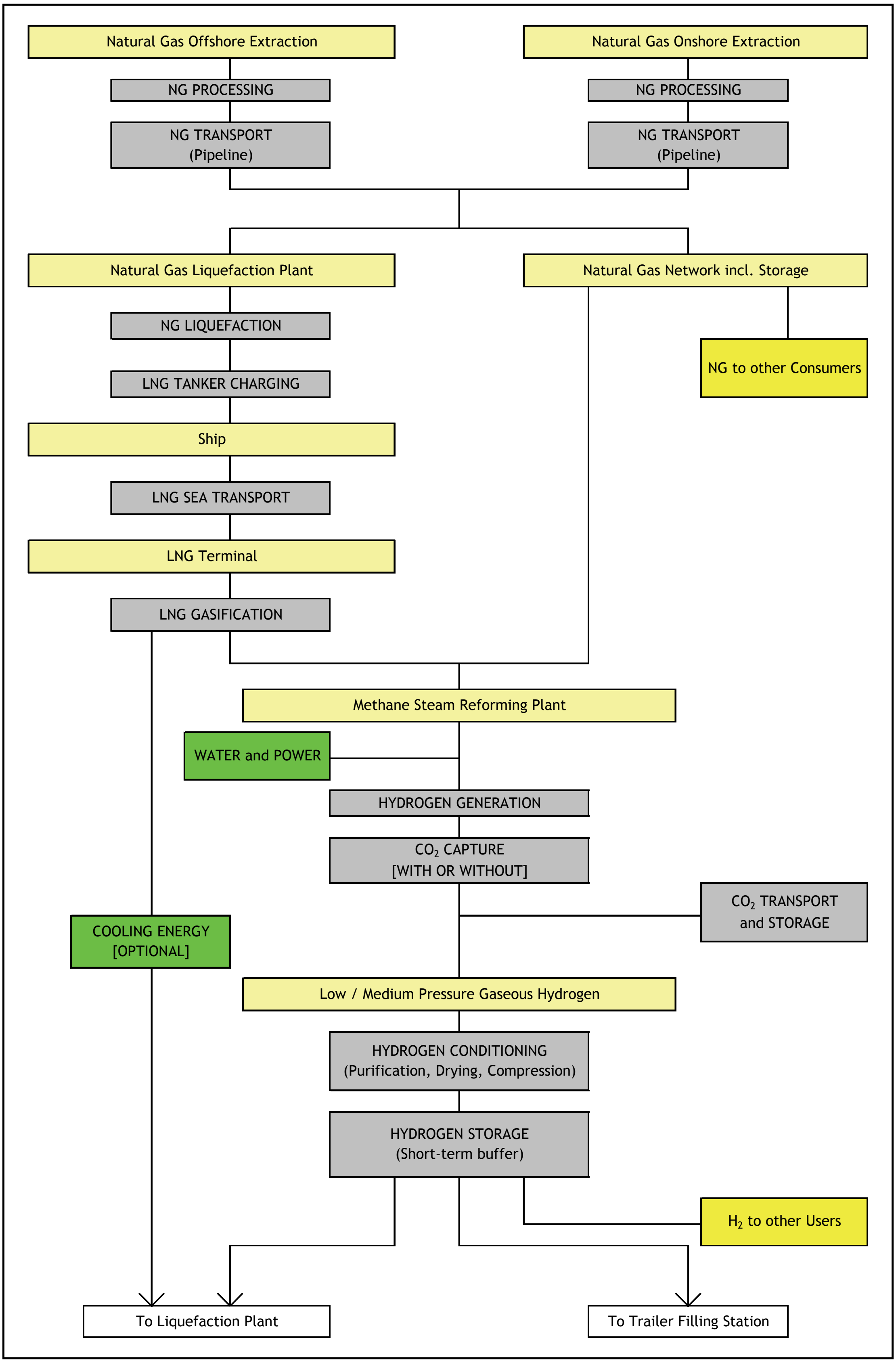


Table 1 Summary of Key Technical Parameters and Default Values for the Production of Hydrogen from Natural Gas by Means of Steam Reforming

Technical Parameter	Units	Default Value
Gross Calorific Value of Onshore Natural Gas (Russia)	MJ/m^3	38.8
Net Calorific Value of Onshore Natural Gas (Russia)	MJ/m^3	34.9
Methane Content of Onshore Natural Gas (Russia)	%	97.0
Carbon Dioxide Content of Onshore Natural Gas (Russia)	%	1.2
Gross Calorific Value of Offshore Natural Gas (Qatar)	MJ/m^3	38.3
Net Calorific Value of Offshore Natural Gas (Qatar)	MJ/m^3	34.5
Methane Content of Offshore Natural Gas (Qatar)	%	74.5
Carbon Dioxide Content of Offshore Natural Gas (Qatar)	%	2.0
Share of Natural Gas Supply from Onshore Sources	%	50
Length of Processed Natural Gas Transmission Pipeline	km	4,196
Loss Rate from Transmission Pipeline	%/km	0.000122
Power Rating of Transmission Pipeline Compressors	MW	170
Average Thermal Efficiency of Compressors	%	26.4
Natural Gas Liquefaction Technology		AP-X
Average Thermal Efficiency of Liquefaction Gas Turbines	%	33.3
Liquefied Natural Gas Ship Round Trip Distance	km	23,369
Re-gasification Technology		SCV
Length of Re-Gasified Natural Gas Transmission Pipeline	km	200
Output Capacity of Steam Reforming Plant	t H_2/a	138,342
CO_2 Generation Rate of Steam Reforming Plant	t CO_2/t H_2	8.80
CO_2 Recovery Rate with Capture	%	71.0
Effective Thermal Efficiency of Steam Reforming Plant:		
- with CO_2 capture	%	78.6
- without CO_2 capture	%	83.9
Natural Gas Requirement of Steam Reforming Plant:		
- with CO_2 capture	MJ/t H_2	176,362
- without CO_2 capture	MJ/t H_2	191,593
Electricity Requirement of Steam Reforming Plant:		
- with CO_2 capture	kWh/t H_2	950
- without CO_2 capture	kWh/t H_2	380

Table 2 Summary of Key Technical Parameters and Default Values for the Carbon Capture and Storage System for Hydrogen Production Plants

Technical Parameter	Units	Default Value
Length of Land CO_2 Pipeline	km	75
Length of Subsea CO_2 Pipeline	km	90
Unit Pressure Drop in CO_2 Pipeline System	bar/km	0.150
Average Efficiency of Supercritical CO_2 Compressors	%	85
Leakage Rate in CO_2 Pipeline System	%/km	0.000026
Number of CO_2 Injection Wells		2
Required Pressure at Bottom of Injection Well	bar	200

3.3 Hydrogen Production by Gasification of Brown Coal

The main features of the process chain represented in the IDEALHY - Brown Coal Gasification V14.xlxs workbook are summarised in Figure 2. The brown coal, which has a relatively high moisture content and low calorific value, is extracted from deposits using surface mining techniques and transported to a coal cleaning and storage plant. It is assumed that no coal drying takes place at this stage given that this provides the feedstock for subsequent gasification involving steam. After transportation to the gasification plant, the clean coal is converted to H_2 (with an assumed purity of 99.500% H_2) and purified using an integrated PSA unit (to 99.99% H_2 purity at 20 bars). Sulphuric acid is also produced as a by-product and CO_2 can either be released to atmosphere or captured for subsequent storage.

The main technical parameters which can be varied in the IDEALHY – Brown Coal Gasification v14.xlxs workbook are summarised as follows:

- Features of surface mining; coal losses and CH_4 leakage,
- Features of raw coal transportation to cleaning and storage plant; mode of transport (road, rail, ship or barge), lorry size, round trip distance and coal losses,
- Features of coal cleaning and storage plant; unit electricity requirement, capacity, annual operating time, life and coal losses,
- Features of clean coal transportation to gasification plant (3 potential stages); mode of transport (road, rail, ship or barge), lorry size, round trip distance and coal losses,
- Characteristics of coal for gasification; gross calorific value, moisture content, carbon content, sulphur content and ash content,
- Features of coal gasification plant; effective thermal efficiency, MDEA solvent consumption rate, Claus catalyst, SCOT activated alumina and SCOT cobalt catalyst make-up rates, coal input capacity rating, availability, life, coal losses and option for CCS,
- Features of CCS system; length of pipeline (overland and subsea), CO_2 leakage rate, number of injection wells and bottom hole pressure, and
- Features of road transportation of ash to disposal; lorry size and round trip distance.

A summary of key technical parameters and the default values adopted in the IDEALHY - Brown Coal Gasification v14.xlxs workbook is given in Table 3. A summary of the key technical parameters and the default values adopted for the CCS system in both the IDEALHY - Natural Gas Steam Reforming v04.xlxs and IDEALHY - Brown Coal Gasification v14.xlxs workbooks has been provided previously in Table 2.

Figure 2 Main Process Chain Features of the MS Excel Workbook for the Production of Hydrogen from Brown Coal by Means of Gasification

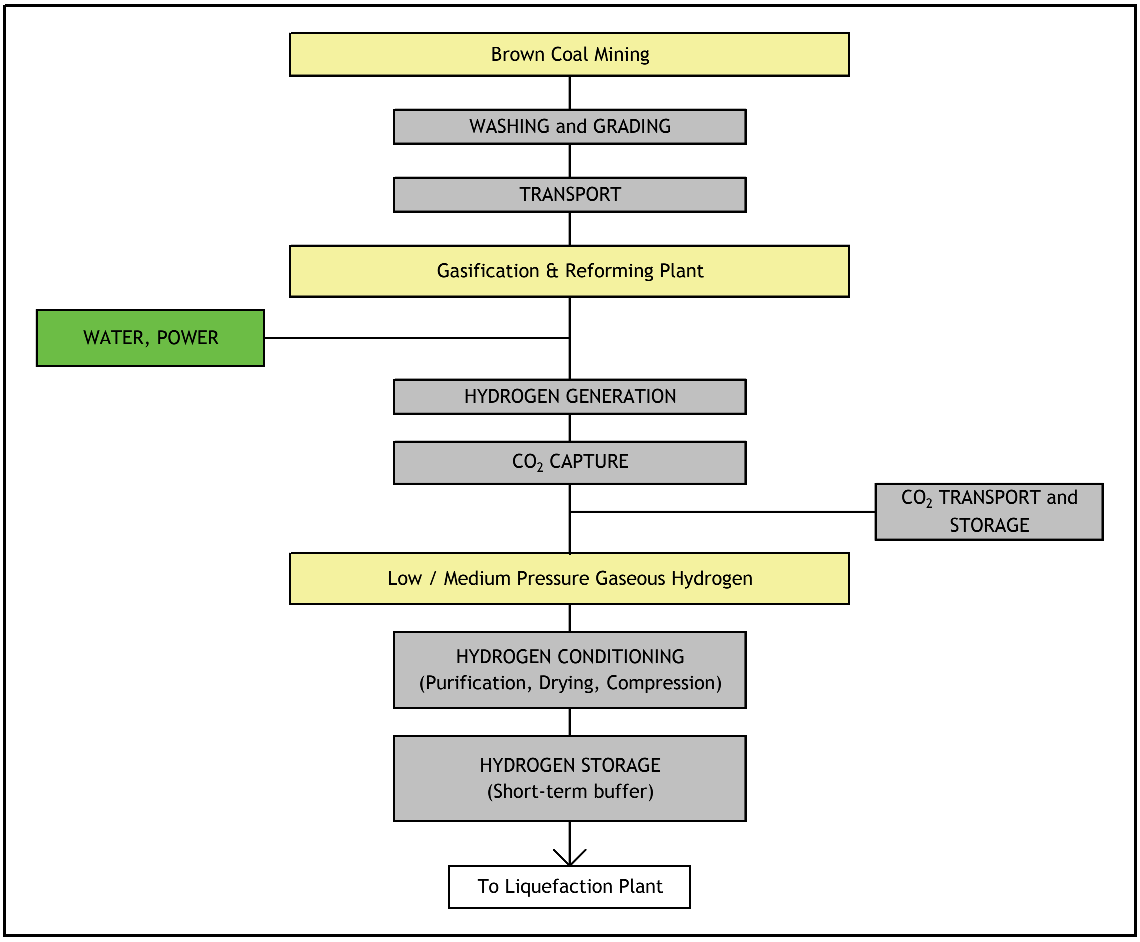


Table 3 Summary of Key Technical Parameters and Default Values for the Production of Hydrogen from Brown Coal by Means of Gasification

Technical Parameter	Units	Default Value
Net Calorific Value of Raw Brown Coal (Australia)	MJ/t	6,800
Methane Emission Rate of Brown Coal Surface Mining (Australia)	kg CH_4/t	0.0333
Road Transport Round Trip Distance to Coal Cleaning Plant	km	100
Electricity Requirement of Coal Cleaning Plant	kWh/t	0.219
Rail Transport Round Trip Distance to Coal Gasification Plant	km	100
Gross Calorific Value of Clean Brown Coal; wet basis (Australia)	MJ/t	12,950
Moisture Content of Clean Brown Coal; wet basis (Australia)	%	50.00
Carbon Content of Clean Brown Coal; wet basis (Australia)	%	34.00
Sulphur Content of Clean Brown Coal; wet basis (Australia)	%	0.15
Ash Content of Clean Brown Coal; wet basis (Australia)	%	1.00
Coal Gasification Plant Capacity	t coal/a	827,802
CO_2 Recovery Rate with Capture	%	92.0
Effective Thermal Efficiency of Coal Gasification Plant:		
- with CO_2 capture	%	60.1
- without CO_2 capture	%	62.3

3.4 Hydrogen Production by Electrolysis Using Wind Power

The main features of the process chain represented in the IDEALHY - Wind Power Electrolysis v13.xlxs workbook are summarised in Figure 3. Electricity is transmitted to the electrolysis plant from the offshore wind farm by subsea and overland cables. Any electricity which is surplus to requirements for distribution to users via the electricity network is used in the electrolysis plant to produce H_2 which is conditioned, compressed and stored in an engineered underground salt cavern situated beneath the electrolysis plant. When the H_2 is required, it is extracted from the salt cavern and dried to provide H_2 (with a 99.999% H_2 purity and at a pressure of 60 bars) for subsequent delivery and use.

The main technical parameters which can be varied in the IDEALHY - Wind Power Electrolysis v13.xlxs workbook are summarised as follows:

- Features of offshore wind farm; number and individual power rating, capacity factor, load factor and life of turbines, and length of array subsea cabling,

- Features of transmission cabling system; length of transmission cabling (subsea and overland), life of cabling and electricity losses,

- Share of electricity used for H_2 production,

- Features of electrolysis plant; efficiency, hydrogen losses, water requirements, source of electricity (for H_2 compressor and dryer), capacity, annual operating time and life of electrolysis plant, and purity and pressure of H_2 output,

- Features of H_2 conditioning and compression plant; H_2 input pressure, H_2 losses, and capacity factor and life of compressor,

- Features of engineered underground salt cavern storage; storage capacity and pressure, and H_2 losses and cushion gas requirements, and

- Features of H_2 drying plant; capacity, electricity requirement, source of electricity and H_2 losses,

A summary of key technical parameters and the default values adopted in the IDEALHY - Wind Power Electrolysis v13.xlxs workbook is given in Table 4.

Figure 3 Main Process Chain Features of the MS Excel Workbook for the Production of Hydrogen from Surplus Electricity from Offshore Wind Power by Means of Electrolysis

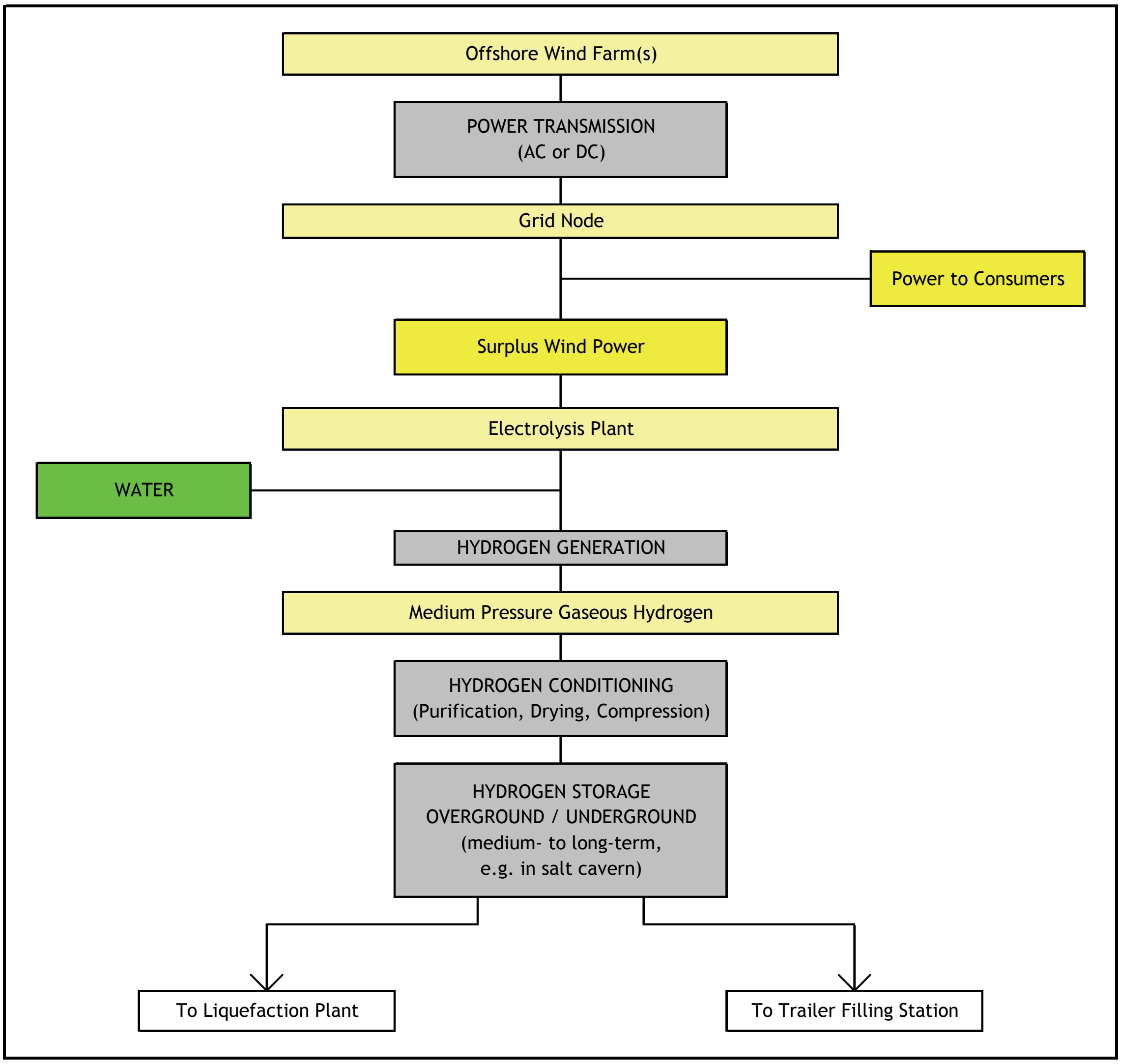


Table 4 Summary of Key Technical Parameters and Default Values for the Production of Hydrogen from Wind Power by Means of Electrolysis

Technical Parameter	Units	Default Value
Total Maximum Power Rating of Offshore Wind Farm	MW	80 x 2
Average Capacity Factor of Wind Turbines	%	95
Average Load Factor of Wind Turbines	%	46
Average Life of Wind Turbines	a	20
Total Length of Array Subsea 30 kV Cabling	km	53
Total Length of Subsea Transmission 150 kV Cabling	km	20
Total Length of Overland Transmission 150 kV Cabling	km	34
Losses from Transmission System	%	1.55
Average Life of Transmission System	a	40
Capacity Rating of Electrolyser	MW	3 x 1
Output Rating of Electrolyser	kg H_2/MW.d	430
H_2 Losses in Electrolyser	%	0
Water Requirements of Electrolyser	t/t H_2	9
Capacity Factor of Electrolyser	%	85
Average Life of Electrolyser	a	25
H_2 Output Pressure from Electrolyser	bar	70
H_2 Losses in Conditioning Compressor	%	1.00
Capacity Adjustment Factor of Conditioning Compressor	%	150
Average Life of Conditioning Compressor	a	30
Capacity of Salt Cavern Storage	t H_2	4,000
Pressure of Salt Cavern Storage	bar	180
Cushion Gas Allowance of Salt Cavern Storage	%	60
Capacity of Drying Plant	MW	1.5
Electricity Requirement of Drying Plant	kWh/t H_2	0.100
H_2 Losses in Drying Plant	%	0
Average Life of Drying Plant	a	25

3.5 Hydrogen Production by Electrolysis Using Solar Power

The main features of the process chain represented in the IDEALHY - Solar Power Electrolysis v09.xlxs workbook are summarised in Figure 4. Electricity is generated by means of a mirror-concentrated solar power tower and transmitted overland to a centralised electrolysis plant where the H_2 is generated. Following drying, H_2 (with a 99.999% H_2 purity and at a pressure of 70 bars) is available for delivery and use.

The main technical parameters which can be varied in the IDEALHY - Solar Power Electrolysis v09.xlxs workbook are summarised as follows:

- Features of solar power tower; annual insolation, power rating, capacity factor and life,

- Features of transmission cabling system; length, capacity, electricity losses and life of transmission cabling (overland),

- Features of electrolysis plant; efficiency, hydrogen losses, water requirements, source of electricity (for H_2 dryer), size, capacity, annual operating hours and life of electrolysis plant, and purity and pressure of H_2 output,

- Features of H_2 drying plant; electricity requirement, source of electricity, drying efficiency, size and H_2 losses,

A summary of key technical parameters and the default values adopted in the IDEALHY - Solar Power Electrolysis v09.xls workbook is given in Table 5.

Figure 4 Main Process Chain Features of the MS Excel Workbook for the Production of Hydrogen from Electricity from Solar Power by Means of Electrolysis

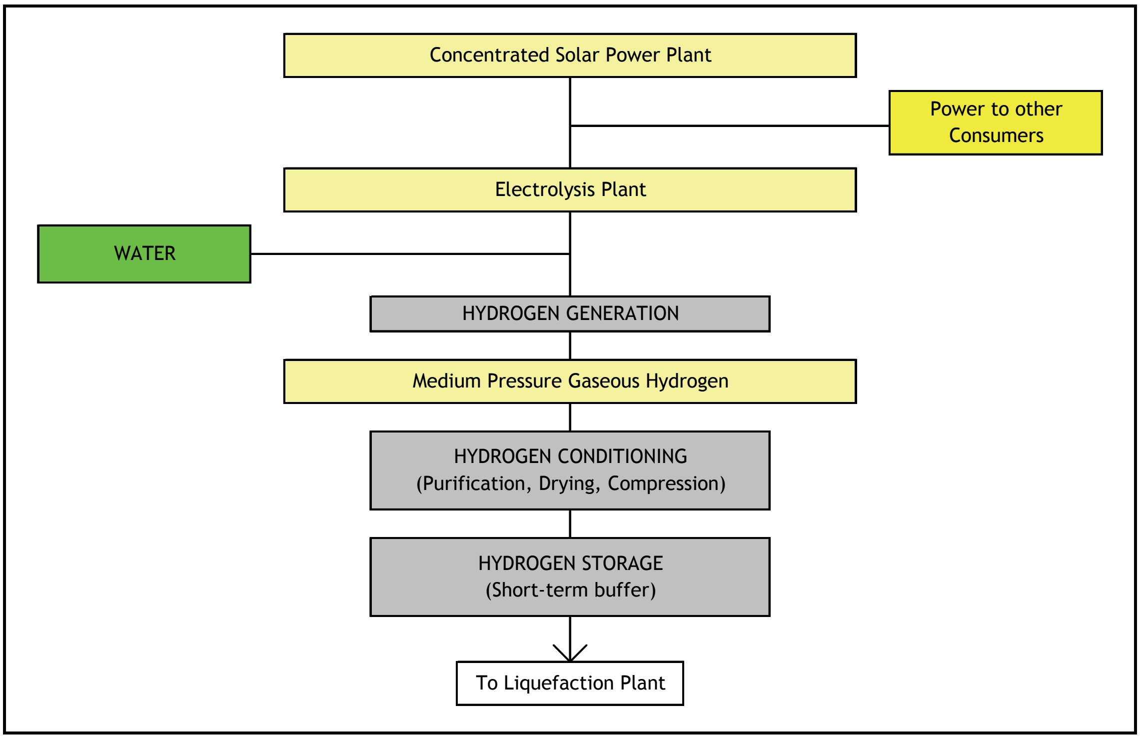


Table 5 Summary of Key Technical Parameters and Default Values for the Production of Hydrogen from Solar Power by Means of Electrolysis

Technical Parameter	Units	Default Value
Average Insolation	h/a	2,850
Total Maximum Power Rating of Solar Power Tower	MW	10
Average Capacity Factor of Solar Power Tower	%	98
Average Life of Solar Power Tower	a	30
Total Length of Overland Transmission 400 kV Cabling	km	100
Maximum Capacity of Overland Transmission 400 kV Cabling	MW	700
Losses from Overland Transmission 400 kV Cabling	%/100 km	2.6
Average Life of Overland Transmission 400 kV Cabling	a	40
Output Rating of Electrolyser	kg H_2/MW.d	430
H_2 Losses in Electrolyser	%	0
Water Requirements of Electrolyser	t/t H_2	9
Capacity Factor of Electrolyser	%	85
Average Life of Electrolyser	a	25
H_2 Output Pressure to Electrolyser	bar	70
Capacity of Drying Plant	MW	1.5
Electricity Requirement of Drying Plant	kWh/t H_2	0.100
H_2 Losses in Drying Plant	%	0
Average Life of Drying Plant	A	25

3.6 Hydrogen Delivery and Utilisation in Fuel Cell Vehicles

The main features of the process chain represented in the IDEALHY - Liquid Hydrogen Delivery v06.xlxs and IDEALHY – Hydrogen Utilisation v04.xlxs workbooks are summarised in Figure 5. Following liquefaction, LH_2 can either be transported by road in tankers to an export shipping terminal or delivered directly to a H_2 refuelling station. If sent to an export terminal, the LH_2 is stored awaiting transfer to a specially-designed ship which transports LH_2 to an import terminal where it may also be stored. Subsequent delivery to a refuelling station is by LH_2 road tanker. Upon arrival at the H_2 refuelling station, the LH_2 is stored in underground tanks prior to pressurisation and evaporation followed by dispensing as gaseous H_2 into fuel cell cars or buses.

The main technical parameters which can be varied in the IDEALHY - Liquid Hydrogen Delivery v06.xlxs and IDEALHY – Hydrogen Utilisation v04.xlxs workbooks are summarised as follows:

- Features of the LH_2 road tanker; capacity,

- Features of LH_2 road tanker delivery to export terminal; round trip distance and H_2 losses,

- Features of LH_2 storage at export terminal; storage capacity and H_2 losses,

- Features of LH_2 ship transport; capacity and fuel consumption of ship, round trip distance and H_2 losses,

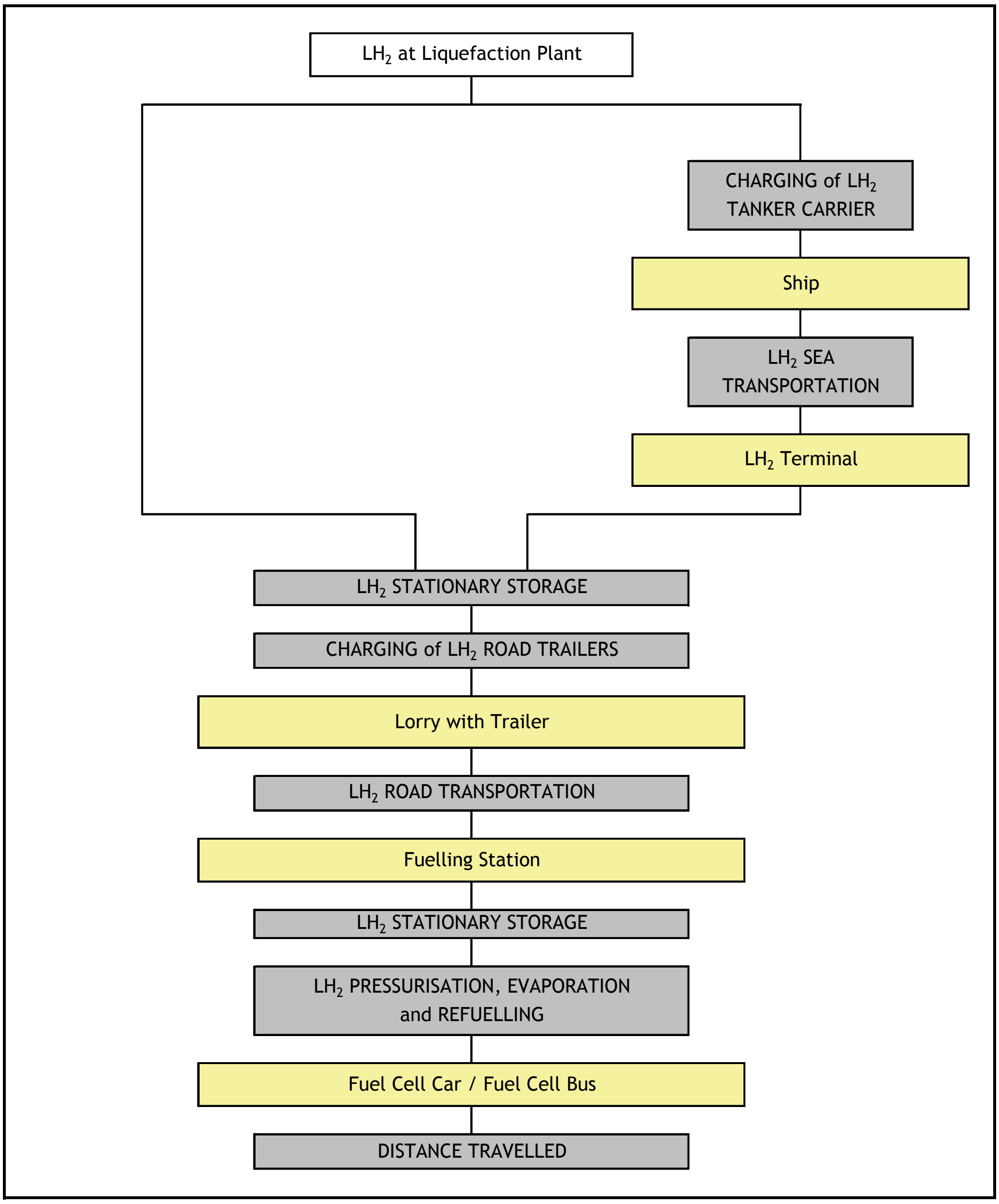
- Features of LH_2 storage at import terminal; storage capacity and H_2 losses,

- Features of LH_2 road tanker delivery to H_2 refuelling station; round trip distance and H_2 losses,

- Features of H_2 refuelling station; H_2 supply rate, H_2 losses in storage and re-gasification pressure, and

- Features of fuel cell car; H_2 refuelling and on-board storage pressure, onboard storage H_2 losses, fuel consumption rate and life.

Figure 5 Main Process Chain Features of the MS Excel Workbook for the Utilisation of Hydrogen in Fuel Cell Cars and Buses with Delivery in Liquefied Hydrogen Tanker



A summary of key technical parameters and the default values adopted for the LH_2 delivery system in the IDEALHY - Liquid Hydrogen Delivery v06.xlxs workbook is given in Table 6. It should be noted that the LH_2 road tankers are assumed to be diesel-fuelled and the LH_2 ship is assumed to be marine gas oil -fuelled. A summary of the key technical parameters and the default values adopted for fuel cell vehicle utilisation in the IDEALHY - Hydrogen Utilisation v04.xlxs is provided in Table 7.

Table 6 Summary of Key Technical Parameters and Default Values for Liquid Hydrogen Delivery

Technical Parameter	Units	Default Value
H_2 Losses in Transfer of LH_2 Road Tanker	%	0
Round Trip Distance for Road Tanker Delivery to Export Terminal	km	0
H_2 Losses in LH_2 Road Tanker Delivery to Export Terminal	%	1
Capacity of LH_2 Storage at Export Terminal	t H_2	20,260
H_2 Losses in LH_2 Storage at Export Terminal	%	1
Extrapolated Capacity of LH_2 Ship	m^3 H_2	238,500
Fuel Consumption Rate of Marine Gas Oil-fuelled LH_2 Ship	MJ/km	7,197
Round Trip Distance for LH_2 Ship Transport	km	23,365
H_2 Losses in LH_2 Ship Transport	%	1
Capacity of LH_2 Storage at Import Terminal	t H_2	20,260
H_2 Losses in LH_2 Storage at Import Terminal	%	1
Capacity of LH_2 Road Tanker	t H_2	3.50
Round Trip Distance for Road Tanker Delivery to H_2 Refuelling Station	km	100
H_2 Losses in LH_2 Road Tanker Delivery to H_2 Refuelling Station	%	1
H_2 Losses in LH_2 Storage at H_2 Refuelling Station	%	1
H_2 Losses in H_2 Delivery to Fuel Cell Vehicles at H_2 Refuelling Station	%	1
H_2 Re-gasification Pressure at H_2 Refuelling Station	Bar	20
H_2 Supply Rate of H_2 Refuelling Station	kg H_2/d	340

Table 7 Summary of Key Technical Parameters and Default Values for Fuel Cell Vehicles

Technical Parameter	Units	Default Value
On-board Storage Pressure:		
- fuel cell car	bar	700
- fuel cell bus	bar	350
Fuel Consumption Rate:		
- fuel cell car	kg H_2/100 km	0.960
- fuel cell bus	kg H_2/100 km	22.630
Vehicle Life:		
- fuel cell car	km	300,000
- fuel cell bus	km	265,000

The main features of the process chain represented in the IDEALHY Compressed Hydrogen Delivery v06.xlxs workbook are summarised in Figure 6. It is assumed that compressed gaseous hydrogen (GH_2) is transported by diesel-fuelled road in tankers directly to a H_2 refuelling station. Upon arrival at the H_2 refuelling station, the GH_2 is compressed and stored in underground tanks prior to dispensing into fuel cell cars or buses.

The main technical parameters which can be varied in the IDEALHY - Compressed Hydrogen Delivery v06.xlxs and IDEALHY – Hydrogen Utilisation v04.xlxs workbooks are summarised as follows:

- Features of compressed GH_2 road tanker delivery to H_2 refuelling station; type of tanker (steel or composite tube trailer), capacity, round trip distance and H_2 losses,

- Features of H_2 refuelling station; H_2 supply rate, compression pressure, compressor efficiency factor and efficiency, and H_2 losses in storage, and

- Features of fuel cell car; H_2 refuelling and onboard storage pressure, onboard storage H_2 losses, fuel consumption rate and life.

A summary of key technical parameters and the default values adopted for the compressed GH_2 delivery system in the IDEALHY - Compressed Hydrogen Delivery v06.xlxs workbook is given in Table 8. A summary of the key technical parameters and the default values adopted for fuel cell vehicle utilisation in the IDEALHY - Hydrogen Utilisation v04.xlxs workbook has been provided previously in Table 7.

Figure 6 Main Process Chain Features of the MS Excel Workbook for the Utilisation of Hydrogen in Fuel Cell Cars and Buses with Delivery in Compressed Hydrogen Tanker

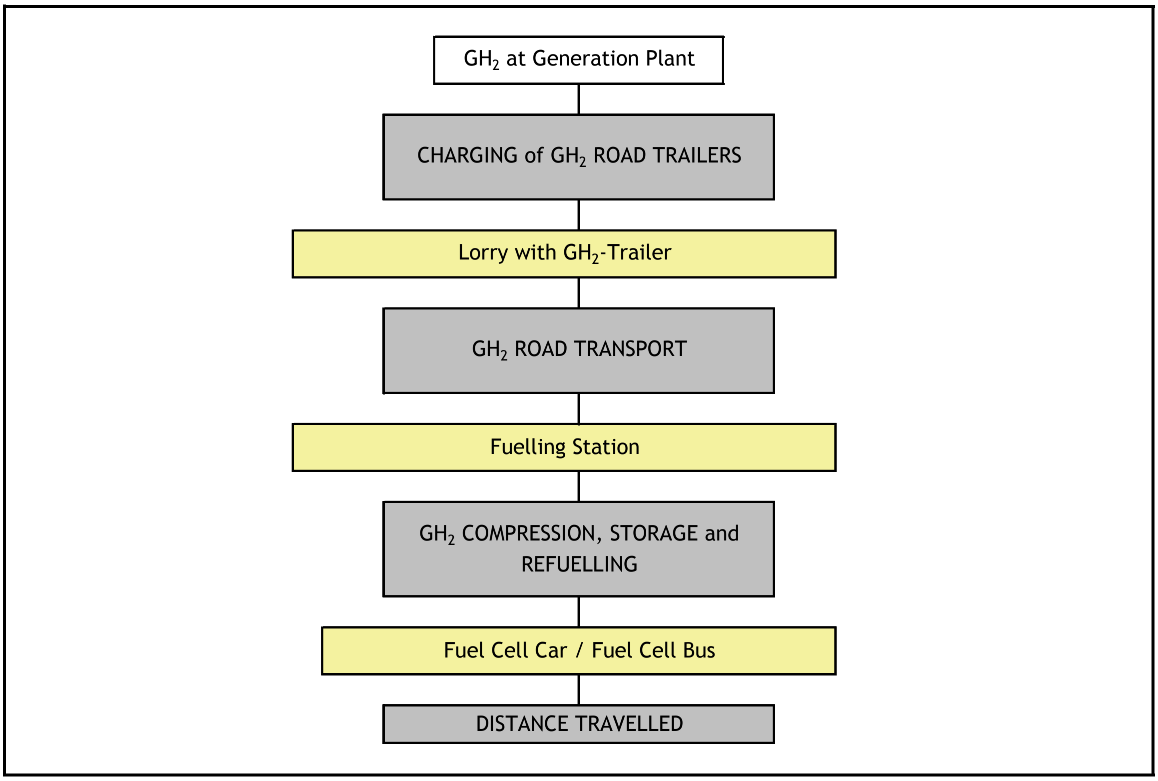


Table 8 Summary of Key Technical Parameters and Default Values for the Compressed Hydrogen Delivery

Technical Parameter	Units	Default Value
Capacity of Compressed GH_2 Steel Tube Trailer Road Tanker	t H_2	0.300
Capacity of Compressed GH_2 Composite Tube Trailer Road Tanker	t H_2	0.800
Round Trip Distance for Road Tanker Delivery to H_2 Filling Station	km	100
H_2 Losses in Compressed GH_2 Road Tanker Delivery to H_2 Refuelling Station	%	1
H_2 Losses in H_2 Storage at H_2 Refuelling Station	%	1
H_2 Losses in H_2 Delivery to Fuel Cell Vehicles at H_2 Refuelling Station	%	1
Compression Pressure for H_2 Storage at H_2 Refuelling Station	Bar	20
Efficiency of Compressor for H_2 Storage at H_2 Refuelling Station	%	85
H_2 Supply Rate of H_2 Refuelling Station	kg H_2/d	340

4. Illustrative Results

4.1 Primary Energy Inputs

Using the default values adopted in the appropriate workbooks, the average estimates of total primary energy inputs for the production of H_2 from relevant sources by specified technologies, derived with the RED and consequential LCA methodologies, are summarised in Table 9. For these results, it is assumed that any electricity supplied from the grid, such as for compression for H_2 storage in a salt cavern, reflects appropriate primary energy multipliers for EU-27 in 2009.

Table 9 Total Primary Energy Inputs for Hydrogen Production: Default Values

Pathway	Total Primary Energy Inputs (MJ/t H_2)	
	RED Methodology	Consequential LCA Methodology
H_2 from Natural Gas by Steam Reforming:		
- without CCS	184,434	192,577
- with CCS	205,991	210,975
H_2 from Brown Coal by Gasification:		
- without CCS	142,263	142,502
- with CCS	175,800	182,157
H_2 from Wind Power by Electrolysis:		
- without salt cavern storage	1,169	23,181
- with salt cavern storage	4,557	27,745
H_2 from Solar Power by Electrolysis	272	77,932

The relative contributions to total primary energy inputs for H_2 production from natural gas by steam reforming, from brown coal by gasification, and from wind power and solar power by electrolysis, based on default values, are shown in Figures 7 to 14, respectively. The most dominant contributions to total primary energy inputs for H_2 production from natural gas and brown coal are from these fossil fuels themselves, regardless of the methodology adopted (see Figures 7 to 10).

Figure 7 Contributions to Total Primary Energy Inputs for Hydrogen Production from Natural Gas by Steam Reforming without and with CCS; Default Values and RED Methodology

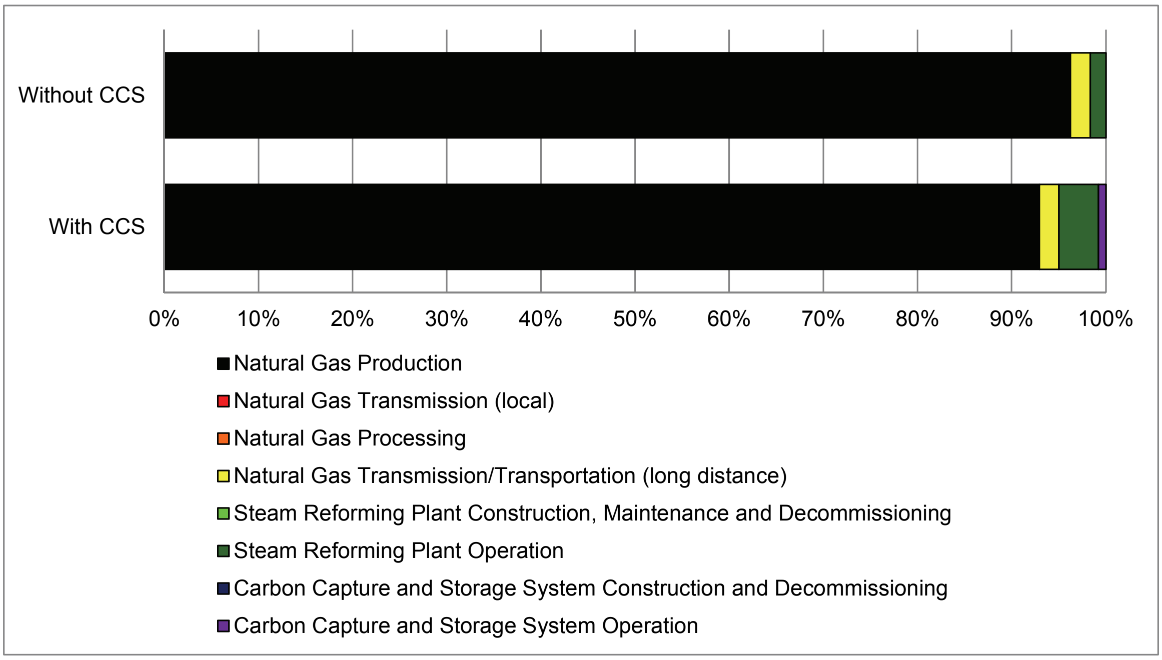


Figure 8 Contributions to Total Primary Energy Inputs for Hydrogen Production from Natural Gas by Steam Reforming without and with CCS; Default Values and Consequential LCA Methodology

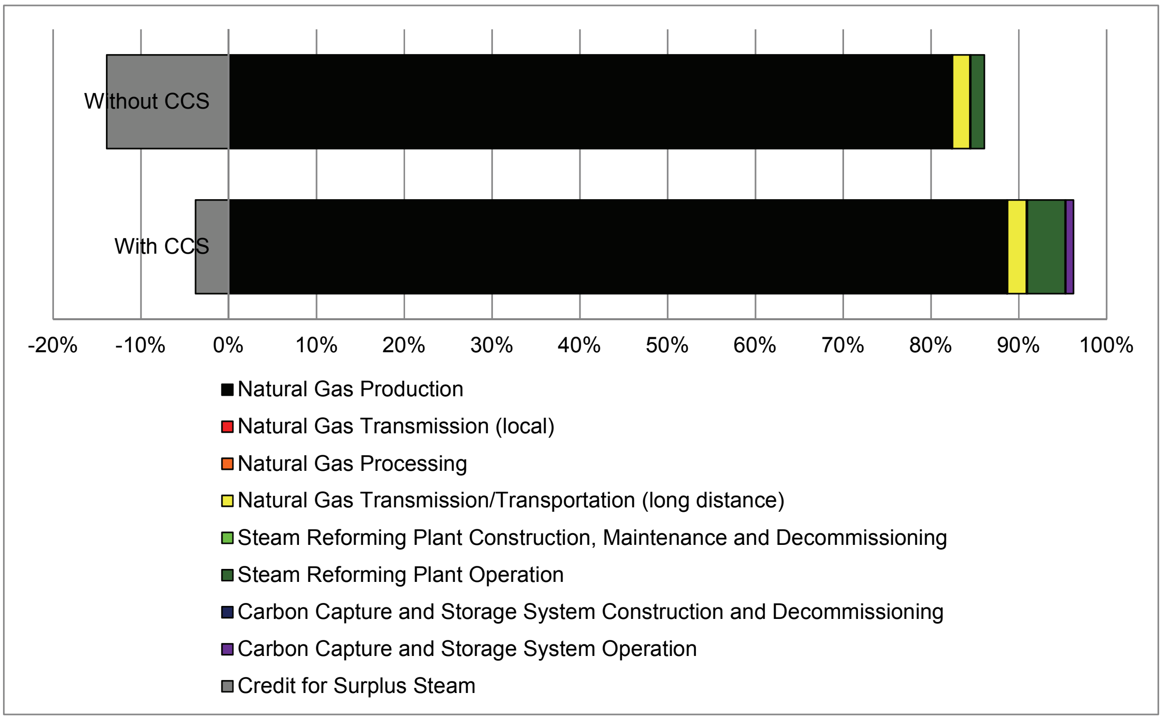


Figure 9 Contributions to Total Primary Energy Inputs for Hydrogen Production from Brown Coal by Gasification without and with CCS; Default Values and RED Methodology

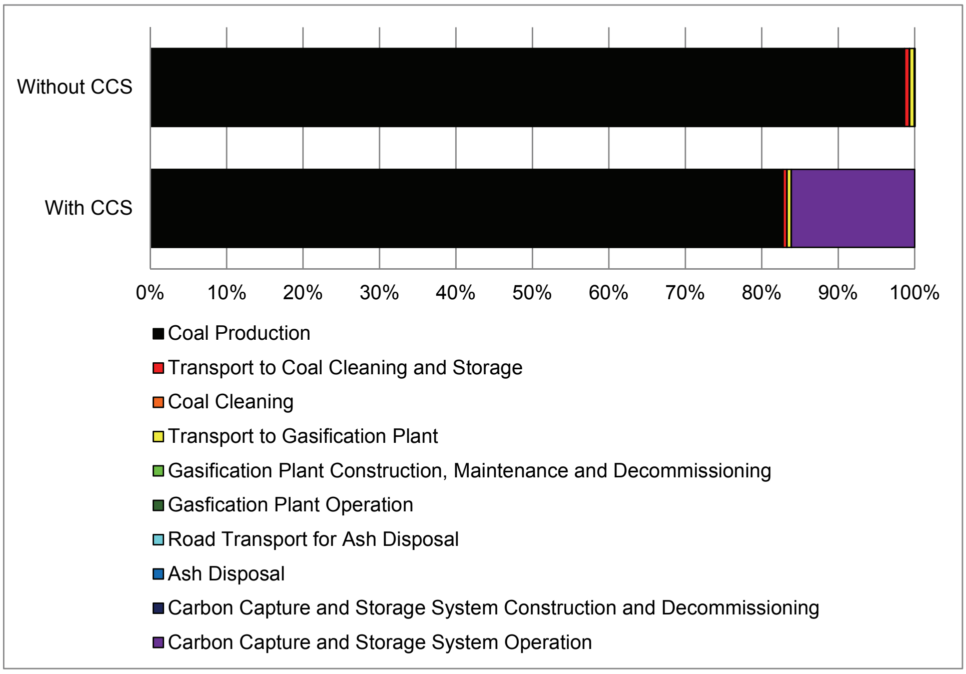
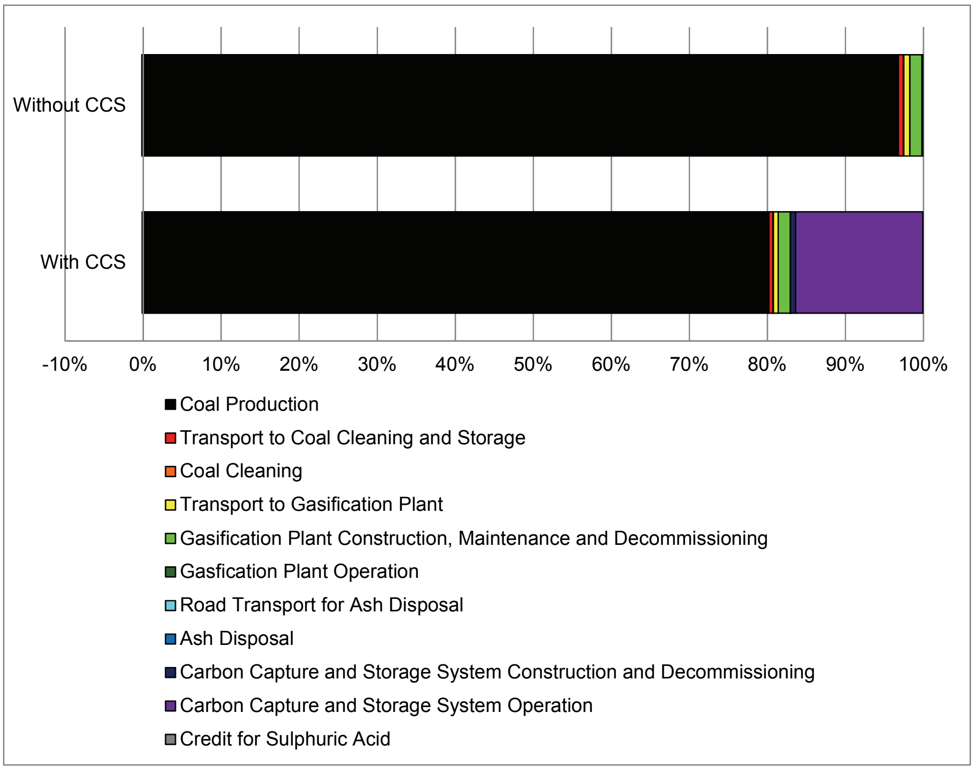


Figure 10 Contributions to Total Primary Energy Inputs for Hydrogen Production from Brown Coal by Gasification; Default Values and Consequential LCA Methodology



With the RED methodology, the most significant contributions to total primary energy inputs to H_2 production from wind power by electrolysis due to the use of EU-27 2009 grid electricity for drying without salt cavern storage, and compression and drying with salt cavern storage (see Figure 11). When the consequential LCA methodology is applied, wind turbine manufacture adds to the main contributions to total primary energy inputs, becoming the dominant contribution in the case without salt cavern storage (see Figure 12).

Figure 11 Contributions to Total Primary Energy Inputs for Hydrogen Production from Wind Power by Electrolysis without and with Salt Cavern Storage; Default Values and RED Methodology

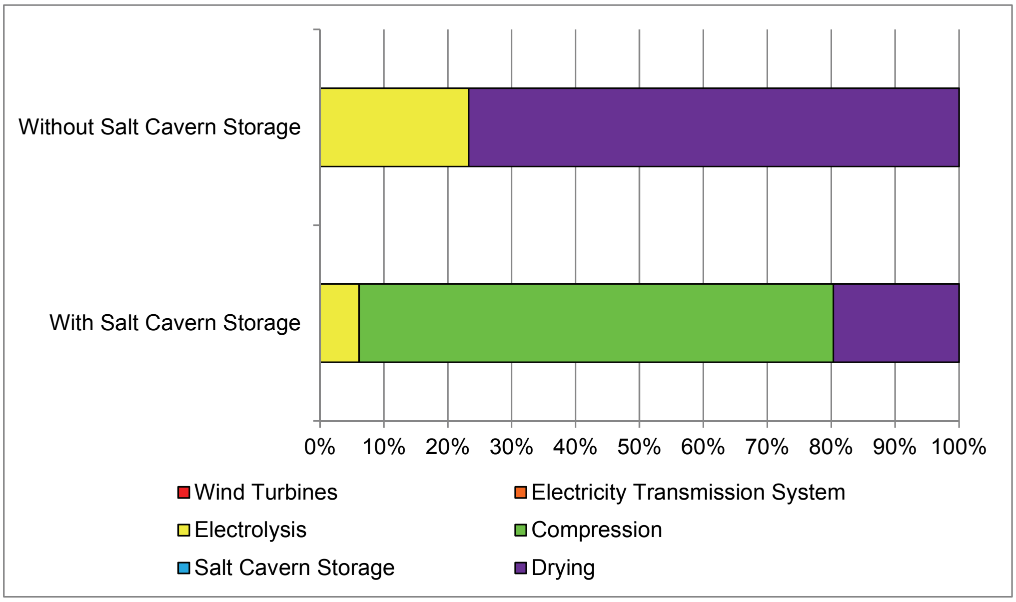
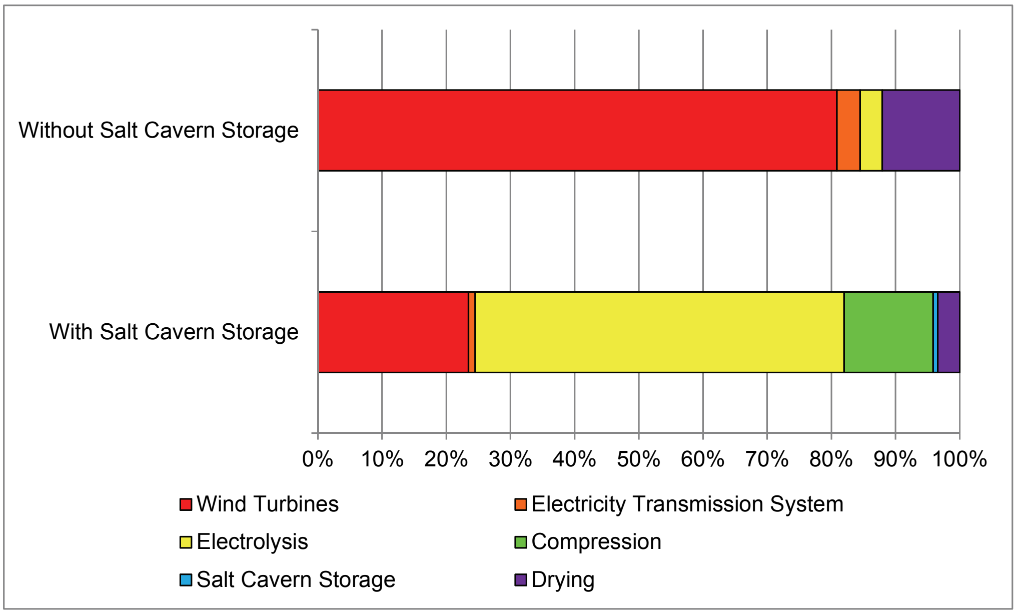


Figure 12 Contributions to Total Primary Energy Inputs for Hydrogen Production from Wind Power by Electrolysis without and with Salt Cavern Storage; Default Values and Consequential LCA Methodology



The only significant contribution to total primary energy inputs to H_2 production from solar power by electrolysis is the supply of water to the electrolyser when the RED methodology is adopted (see Figure 13). Under the consequential LCA methodology, this is almost entirely replaced by solar power tower manufacture and construction as the most important contribution to total primary energy inputs (see Figure 14).

Figure 13 Contributions to Total Primary Energy Inputs for Hydrogen Production from Solar Power by Electrolysis; Default Values and RED Methodology

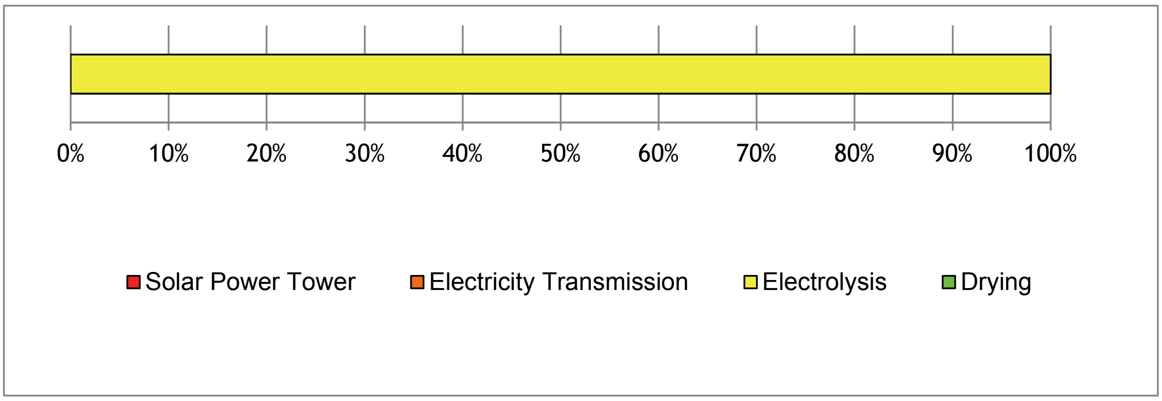
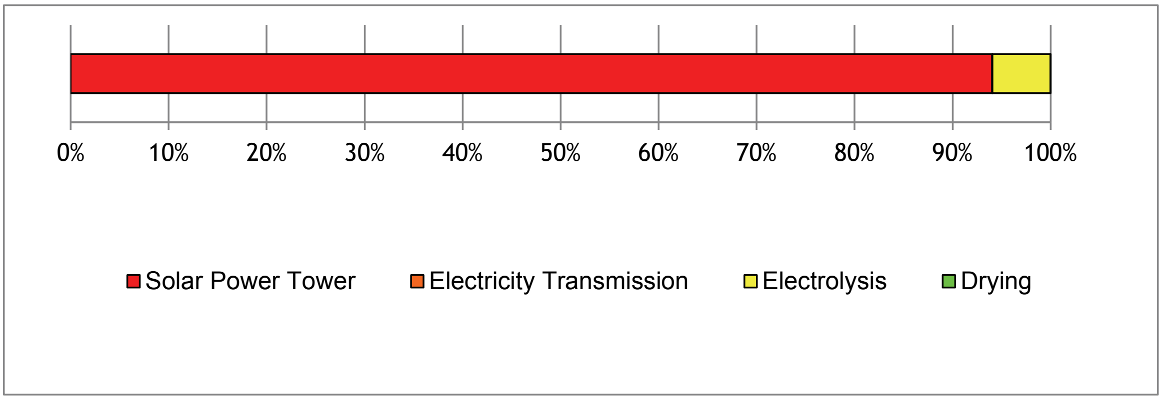


Figure 14 Contributions to Total Primary Energy Inputs for Hydrogen Production from Solar Power by Electrolysis; Default Values and Consequential LCA Methodology



A sample of results illustrating the sensitivities of total primary energy inputs to selected parameters for H_2 production is provided in Figures 15 to 20. The total primary energy inputs for H_2 production from natural gas by steam reforming only vary slightly with the distance over which the feedstock is carried (see Figures 15 and 16). These variations were generated by assuming that natural gas carried by pipeline is derived from onshore deposits, and that natural gas transported by LNG ships is obtained from offshore deposits. In both instances, the variations were based on the distance from the origin of processed natural gas supply to the steam reforming plant. Variations of total primary energy inputs to H_2 production from brown coal by gasification are more sensitive to the distance that the coal is shipped (see Figures 17 and 18). This is due mainly to the relatively lower energy density of coal as a feedstock. The total primary energy inputs to

H_2 production from wind power by electrolysis are markedly sensitive to the load factor of the offshore wind turbines (see Figure 19). Similar sensitivity is seen in the variation of total primary energy inputs to H_2 production from solar power with electrolysis against the level of insolation available to solar power towers (see Figure 20).

Figure 15 Variation of Total Primary Energy Inputs to Hydrogen Production from Natural Gas by Steam Reforming with Transport Distance by Pipeline and LNG Shipping; RED Methodology

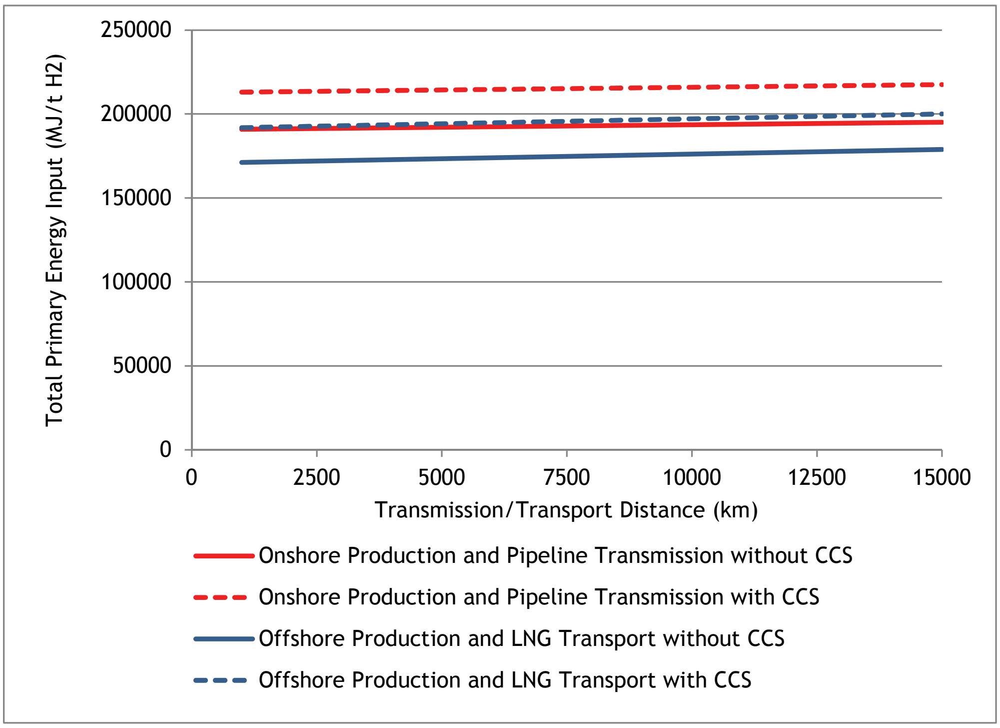


Figure 16 Variation of Total Primary Energy Inputs to Hydrogen Production from Natural Gas by Steam Reforming with Transport Distance by Pipeline and LNG Shipping; Consequential LCA Methodology

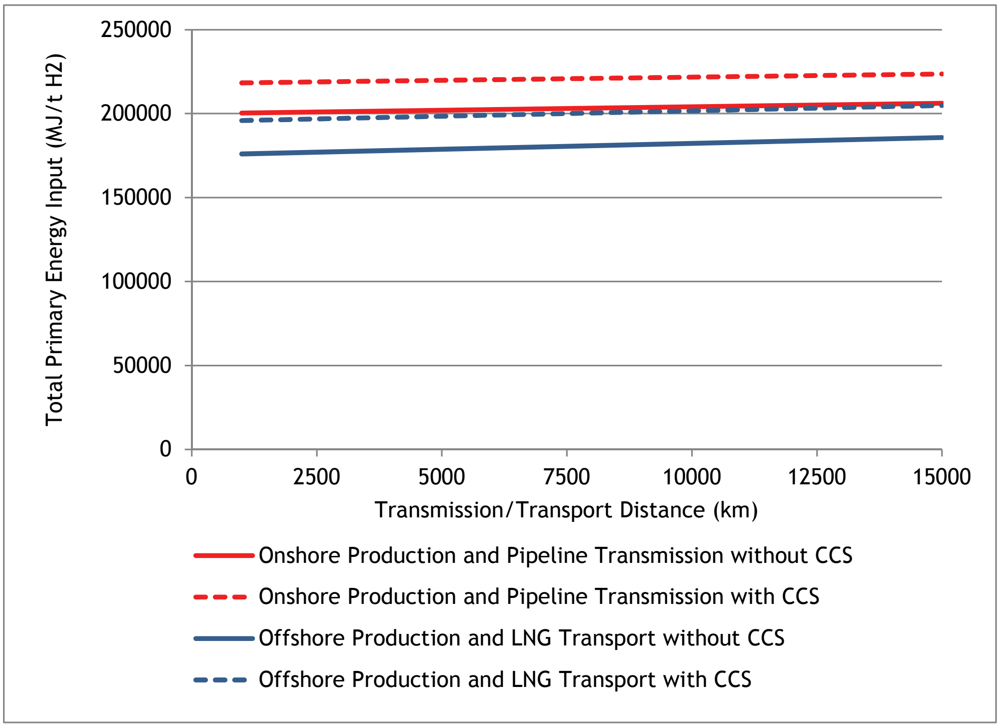


Figure 17 Variation of Total Primary Energy Inputs to Hydrogen Production from Brown Coal by Gasification with Shipping Round Trip Distance; RED Methodology

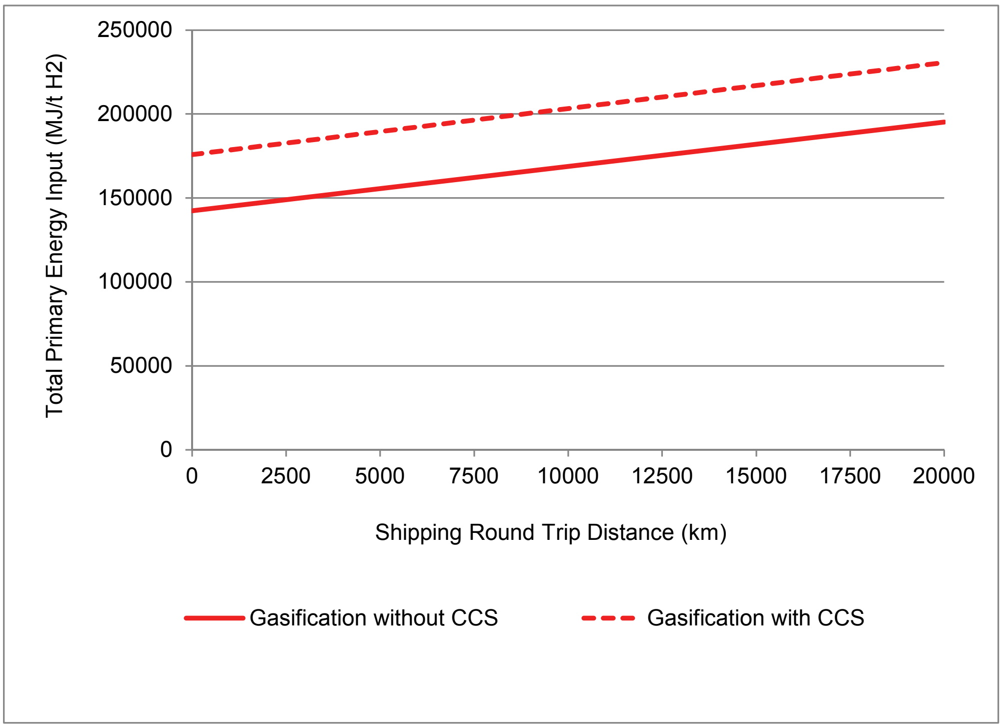


Figure 18 Variation of Total Primary Energy Inputs to Hydrogen Production from Brown Coal by Gasification with Shipping Round Trip Distance; Consequential LCA Methodology

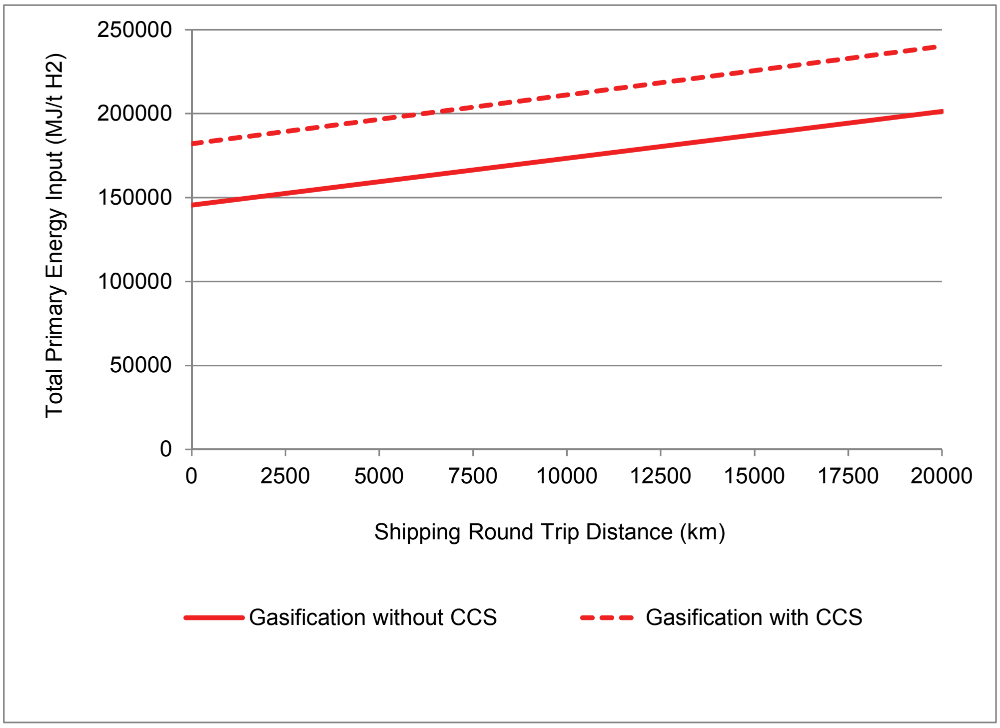


Figure 19 Variation of Total Primary Energy Inputs to Hydrogen Production from Wind Power by Electrolysis with Load Factor; Consequential LCA Methodology

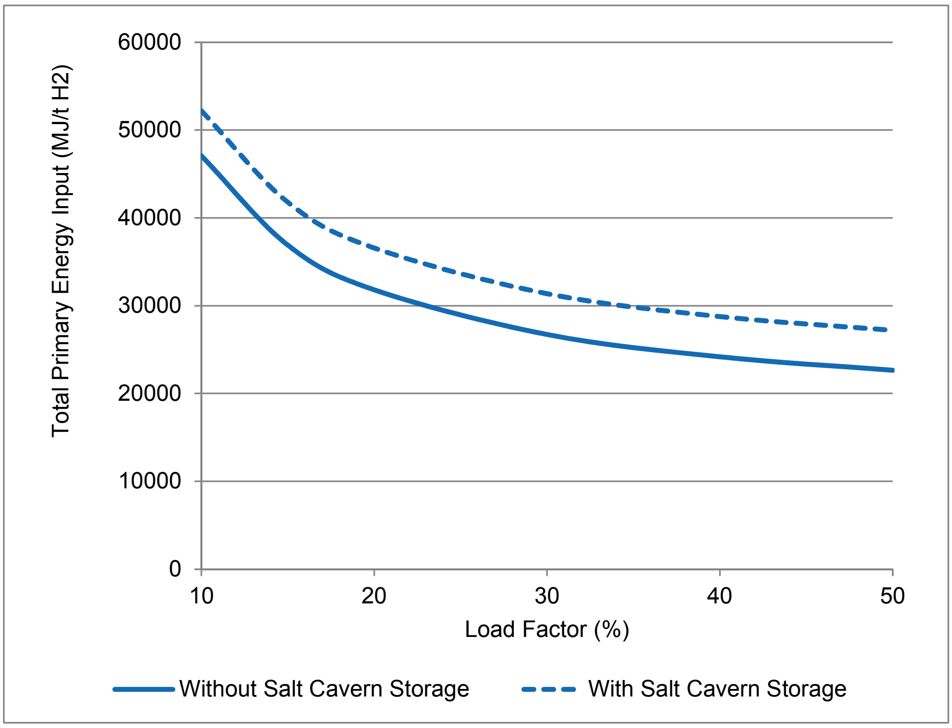
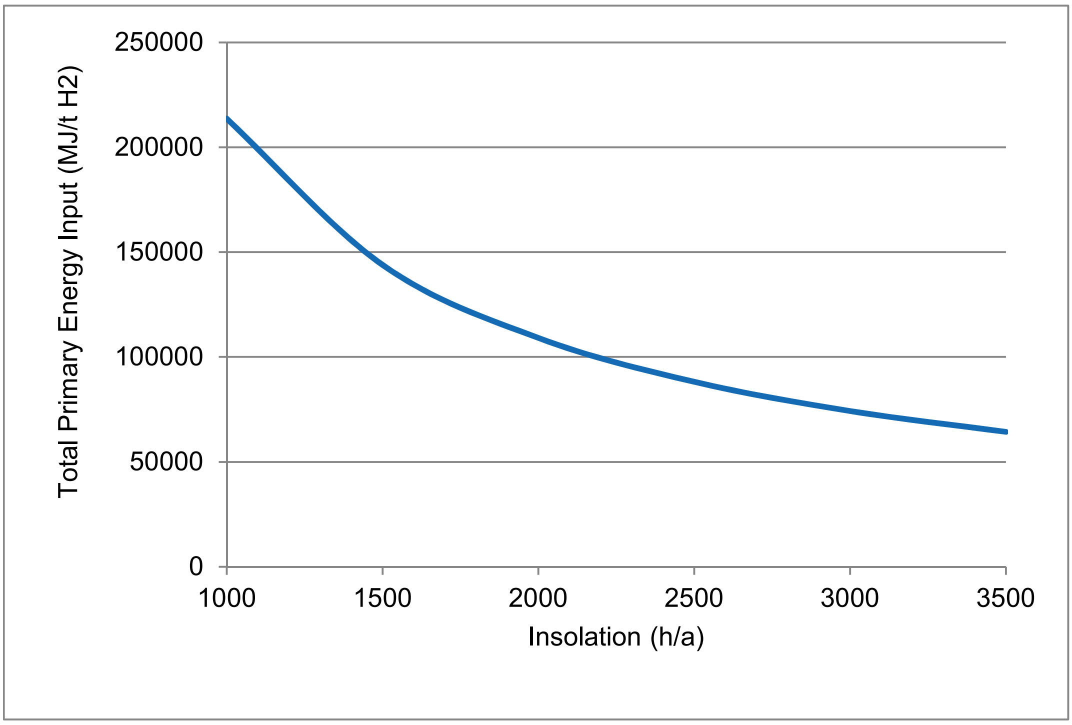


Figure 20 Variation of Total Primary Energy Inputs to Hydrogen Production from Solar Power by Electrolysis with Insolation; Consequential LCA Methodology



Assuming only road transport for hydrogen delivery to refuelling stations and using other default values in the relevant workbooks, the average estimates of total primary energy inputs for LH_2 and GH_2 delivery and refuelling, derived with the RED and consequential LCA methodologies, are summarised in Table 10. These results adopt a value of 100 km for the round trip distance for delivery and, where relevant, the primary energy multiplier for EU-27 grid electricity in 2009. It should be noted that results for LH_2 and GH_2 delivery in Table 10 cannot be compared directly since liquefaction is not taken into account in the former case.

Table 10 Total Primary Energy Inputs for Hydrogen Delivery and Refuelling: Default Values for 100 Kilometre Round Trip Distance by Road Only

Pathway	Total Primary Energy Input (MJ/t H_2)	
	RED Methodology	Consequential LCA Methodology
LH_2 Delivery and Refuelling	6,780	14,633
Compressed H_2 Delivery and Refuelling:		
- Steel Tube Trailer Delivery for Cars	25,869	29,939
- Steel Tube Trailer Delivery for Buses	23,752	27,730
- Composite Tube Trailer Delivery for Cars	25,009	31,929
- Composite Tube Trailer Delivery for Buses	23,739	30,603

Relative contributions for total primary energy inputs to LH_2 delivery and refuelling are shown in Figures 21 and 22, and to GH_2 delivery and refuelling in Figures 23 and 24. It can be seen that the contribution from the refuelling station dominates total energy inputs for LH_2 delivery and refuelling. In contrast, compression makes a significant contribution to the total primary energy inputs to GH_2 delivery and refuelling.

Figure 21 Contributions to Total Primary Energy Inputs for Liquid Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip Distance by Road Only and RED Methodology

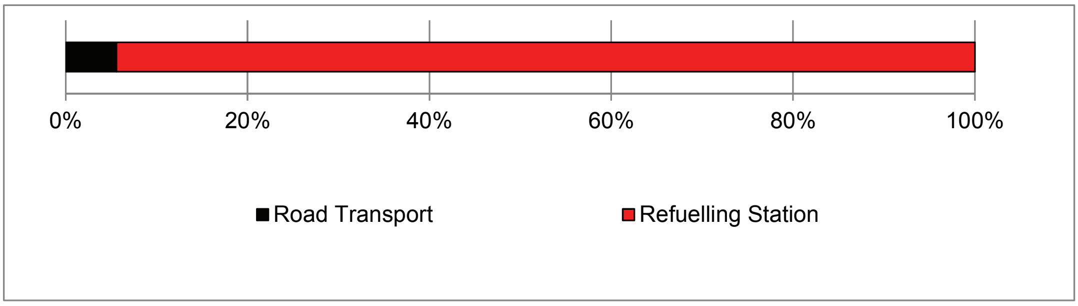


Figure 22 Contributions to Total Primary Energy Inputs for Liquid Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip Distance by Road Only and Consequential LCA Methodology

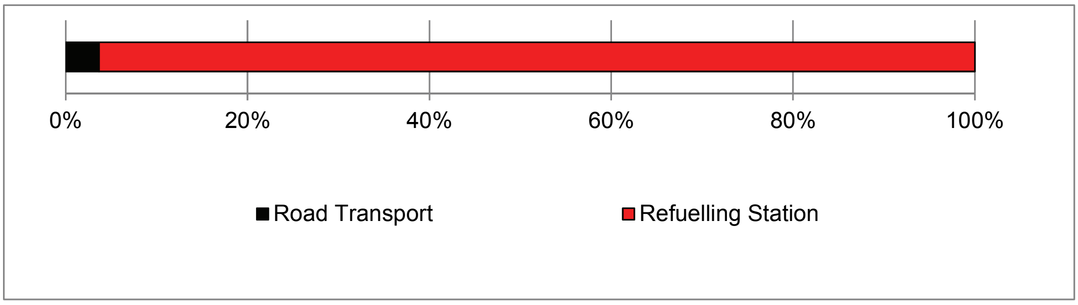


Figure 23 Contributions to Total Primary Energy Inputs for Compressed Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip and RED Methodology

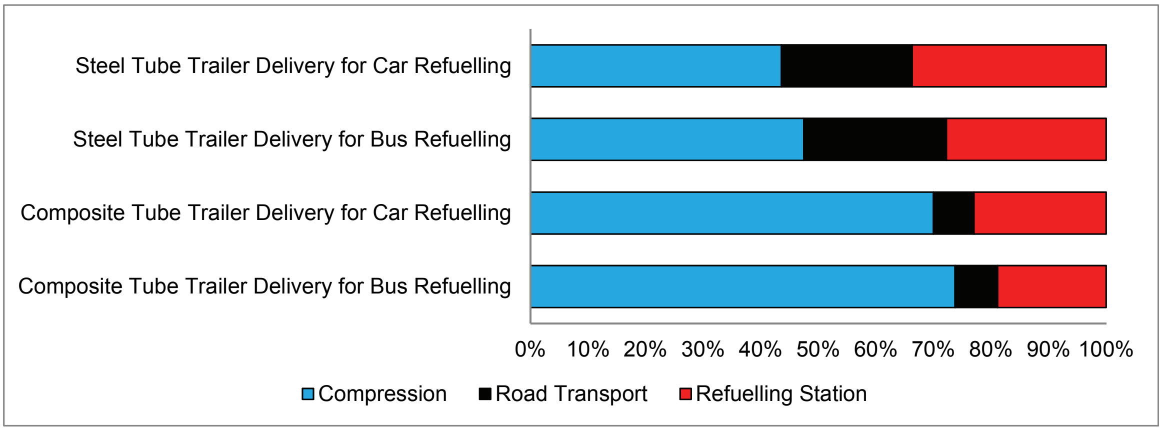
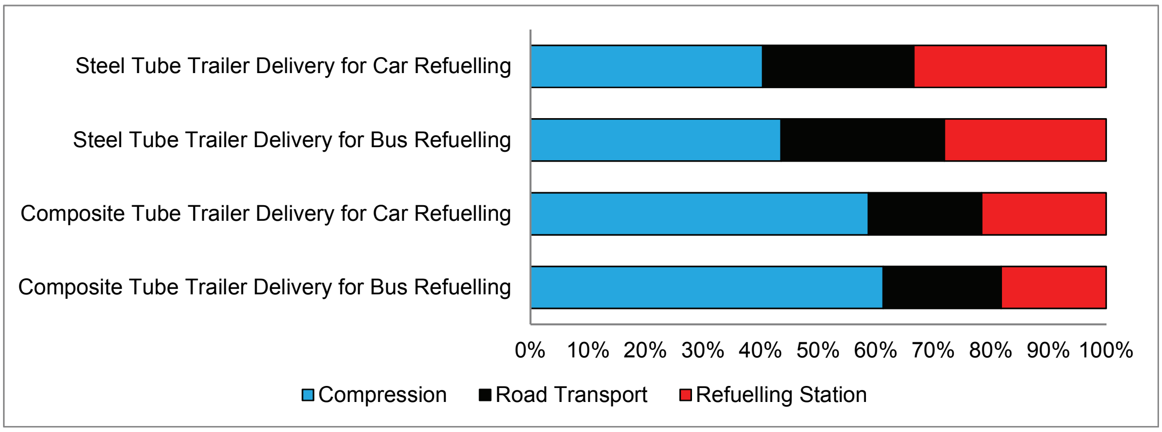


Figure 24 Contributions to Total Primary Energy Inputs for Compressed Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip and Consequential LCA Methodology



A sample of results illustrating the sensitivities of total primary energy inputs to the round trip delivery distance for LH_2 and GH_2 is provided in Figures 25 to 28. Total primary energy inputs to LH_2 delivery and refuelling are moderately sensitive to this distance (see Figures 25 and 26). However, this effect is more pronounced for GH_2 delivery and refuelling (see Figures 27 and 28). This is mainly due to the relative densities of LH_2 and GH_2. Differences in total primary energy inputs for GH_2 delivery by steel tube trailers and composite tube trailers are also demonstrated. In particular, it will be noted that for round trip delivery distances greater than about 100 km, the use of composite tube trailers has lower total primary energy inputs than those of steel tube trailers.

Figure 25 Variation of Total Primary Energy Inputs for Liquid Hydrogen Delivery and Refuelling with Round Trip Distance; Road Only Delivery and RED Methodology

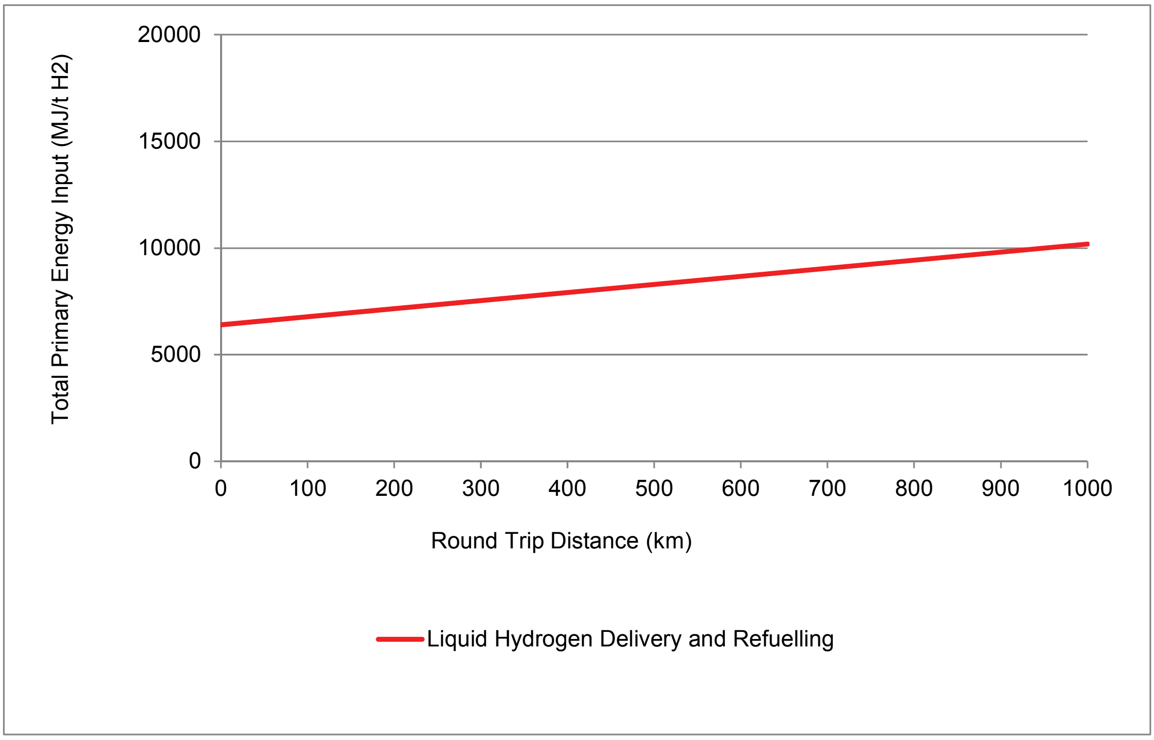


Figure 26 Variation of Total Primary Energy Inputs for Liquid Hydrogen Delivery and Refuelling with Round Trip Distance; Road Only Delivery and Consequential LCA Methodology

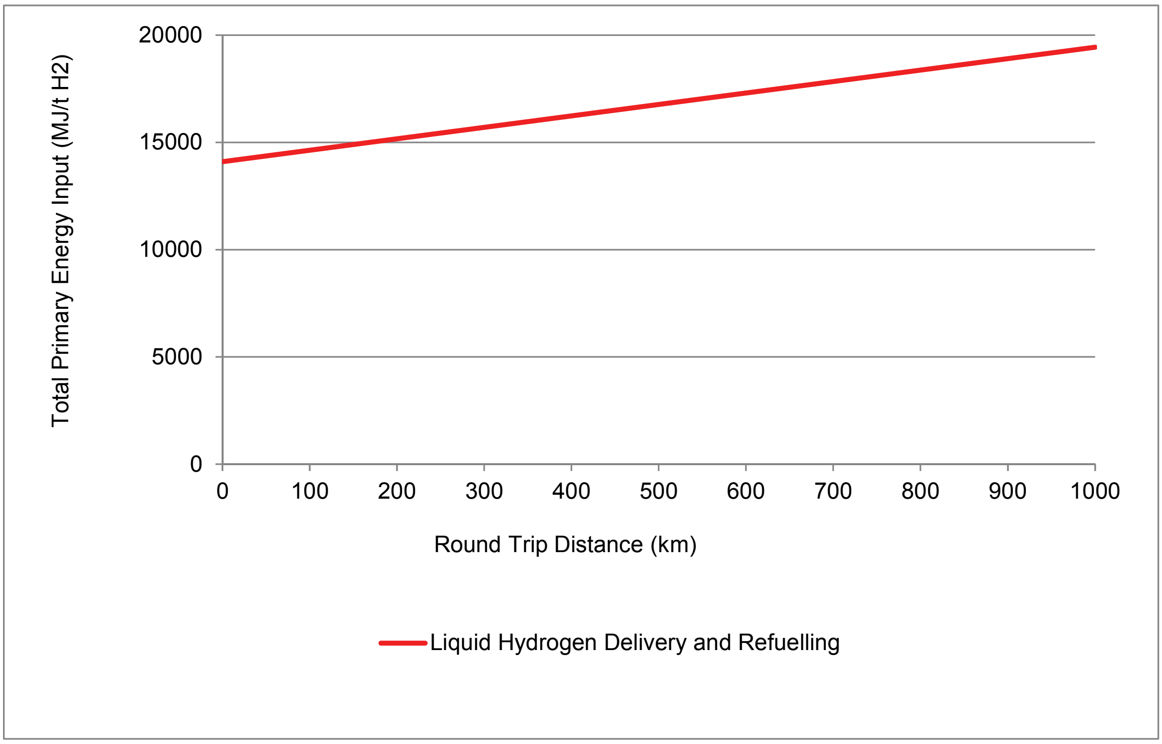


Figure 27 Variation of Total Primary Energy Inputs for Compressed Hydrogen Delivery and Refuelling with Round Trip Distance; RED Methodology

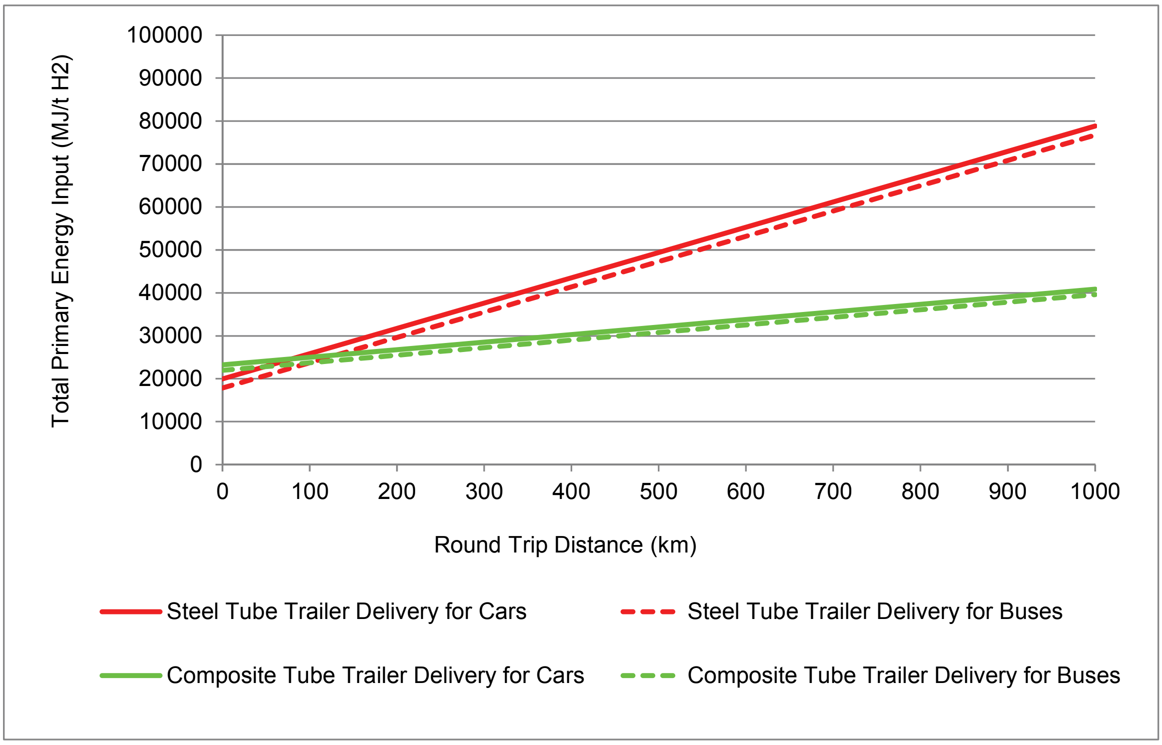
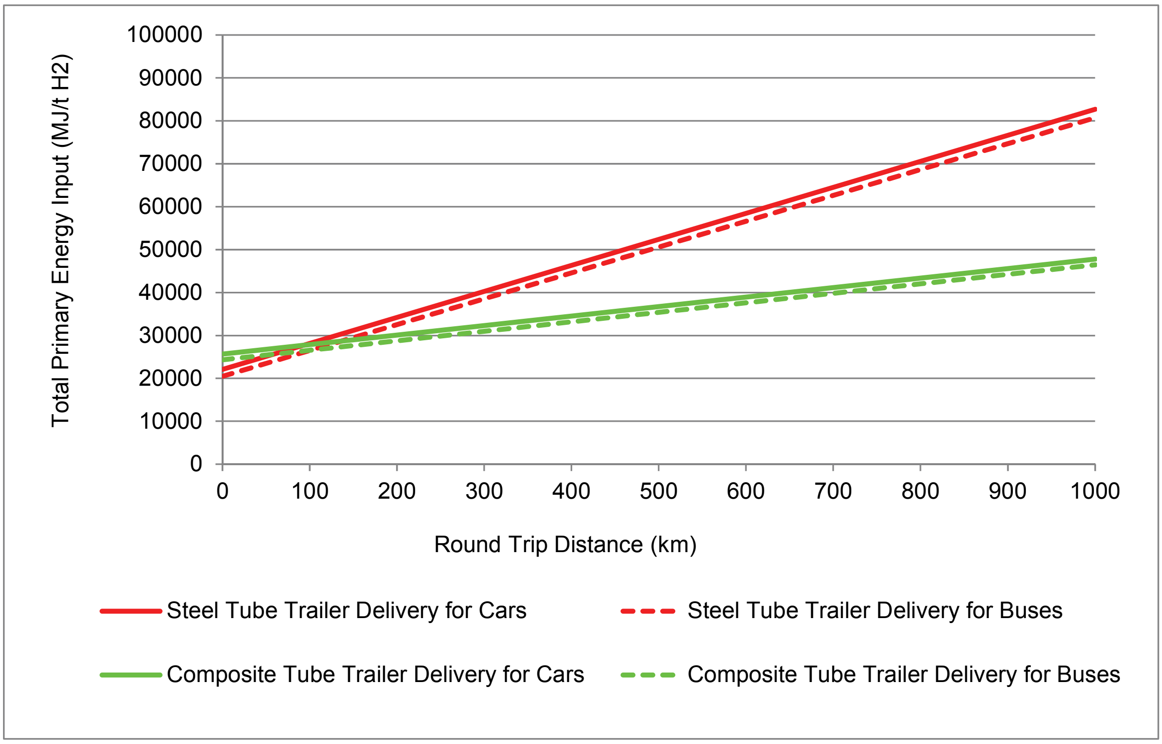


Figure 28 Variation of Total Primary Energy Inputs for Compressed Hydrogen Delivery and Refuelling with Round Trip Distance; Consequential LCA Methodology



Using the default values adopted in the IDEALHY – Hydrogen Utilisation v04.xlxs workbook, estimates of the total primary energy inputs for the manufacture, maintenance and decommissioning of a fuel cell car and bus are summarised in Table 11. These results are based on consequential LCA methodology only because contributions from vehicle manufacture, maintenance and decommissioning are not included with the RED methodology.

Table 11 Total Primary Energy Inputs for Hydrogen Utilisation; Default Values and Consequential LCA Methodology

Pathway	Total Primary Energy Input (MJ/km)
Fuel Cell Car	1.12
Fuel Cell Bus	9.94

4.2 Total Greenhouse Gas Emissions

Using the default values adopted in the appropriate workbooks, the average estimates of total GHG emissions associated with the production of H_2 from relevant sources by specified technologies, derived with the RED and consequential LCA methodologies, are summarised in Table 12. For these results, it is assumed that any electricity supplied from the grid, such as for compression for H_2 storage in a salt cavern, reflects appropriate GHG emissions factors for EU-27 in 2009.

Table 12 Total Greenhouse Gas Emissions for Hydrogen Production: Default Values

Pathway	Total Greenhouse Gas Emissions (kg eq. CO_2/t H_2)	
	RED Methodology	Consequential LCA Methodology
H_2 from Natural Gas by Steam Reforming:		
- without CCS	9,660	10,135
- with CCS	5,299	5,457
H_2 from Brown Coal by Gasification:		
- without CCS	23,854	24,085
- with CCS	5,082	5,571
H_2 from Wind Power by Electrolysis:		
- without salt cavern storage	54	1,663
- with salt cavern storage	190	1,913
H_2 from Solar Power by Electrolysis	18	11,417

The relative contributions to total GHG emissions for H_2 production from natural gas by steam reforming, from brown coal by gasification, and from wind power and solar power by electrolysis, based on default values, are shown in Figures 29 to 36, respectively. The largest contributions to total GHG emissions for H_2 production from natural gas and brown coal are from steam reformer operation (see Figures 29 and 30) and from gasifier operation (see Figures 31 and 32), regardless of whether CCS is used and whichever methodology is adopted. This is due mainly to CO_2 emissions from these operations. Although reduced with the application of CCS, not all CO_2 emissions are captured so that the remaining release to atmosphere can be still large relative to other GHG emissions.

Figure 29 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Natural Gas by Steam Reforming; Default Values and RED Methodology

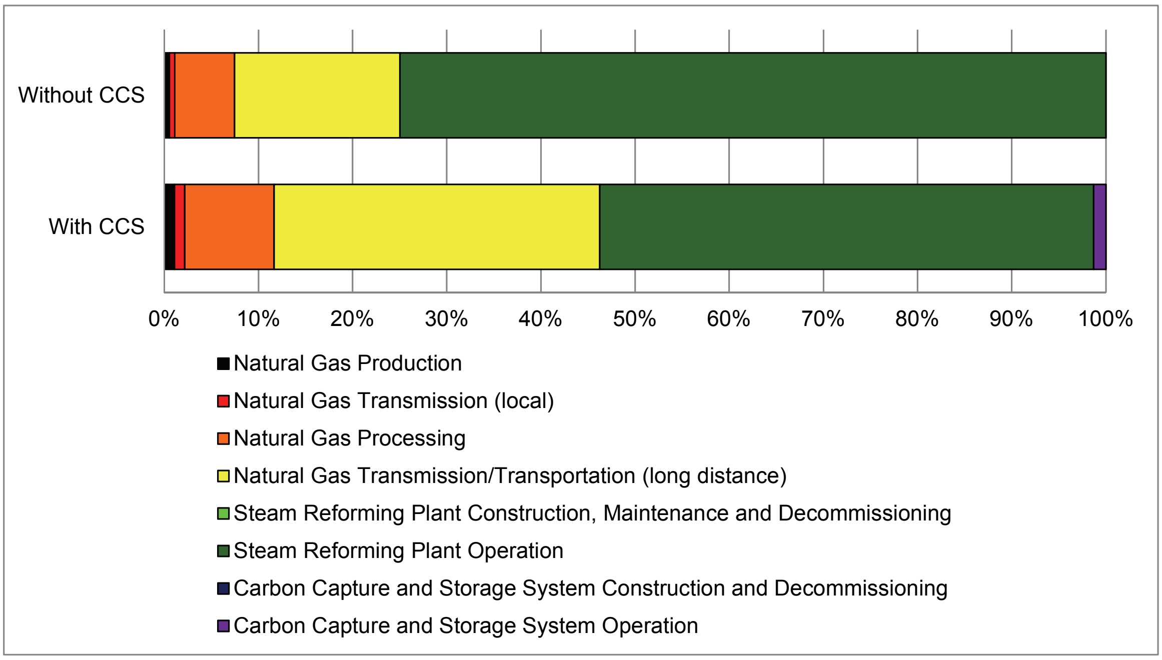


Figure 30 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Natural Gas by Steam Reforming; Default Values and Consequential LCA Methodology

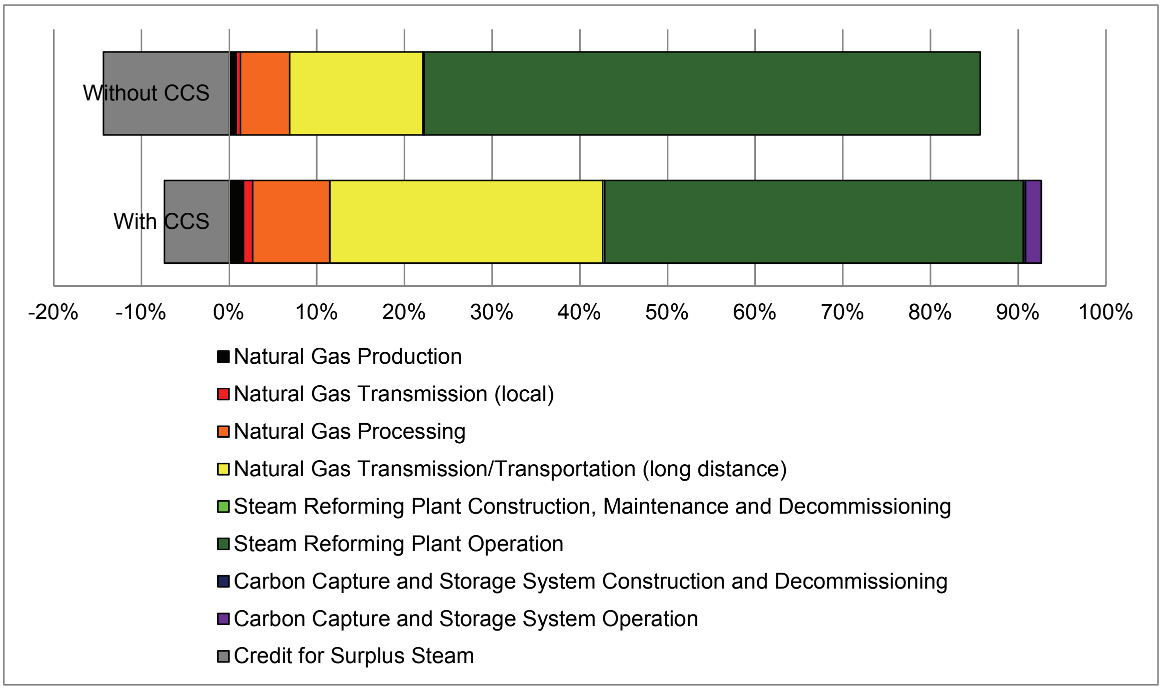


Figure 31 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Brown Coal by Gasification; Default Values and RED Methodology

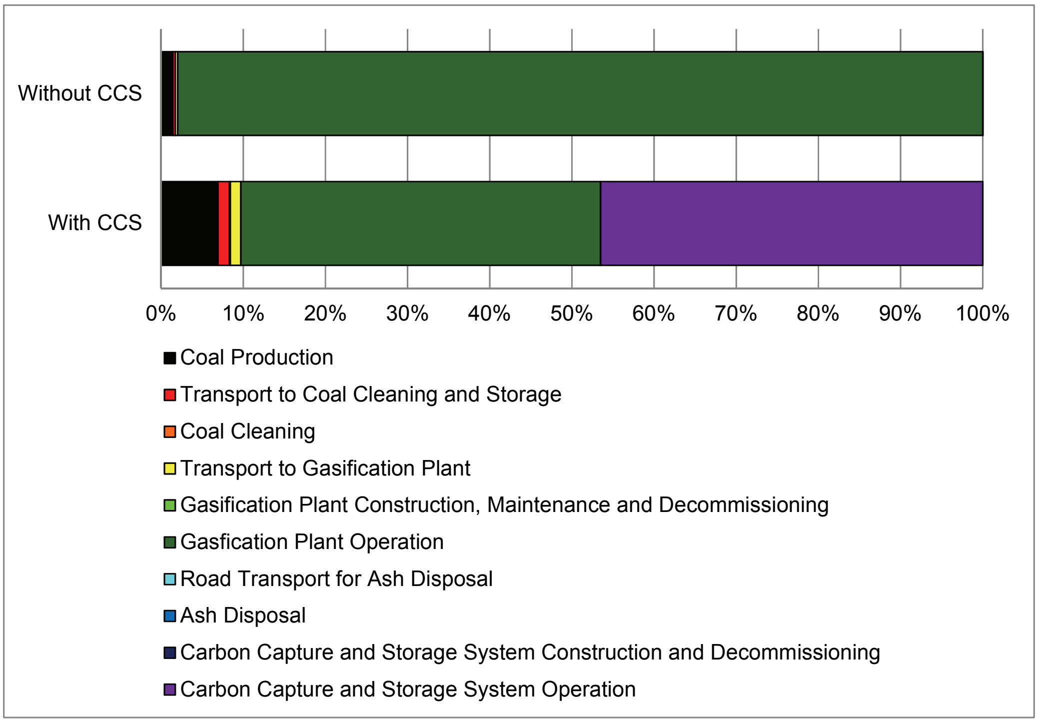
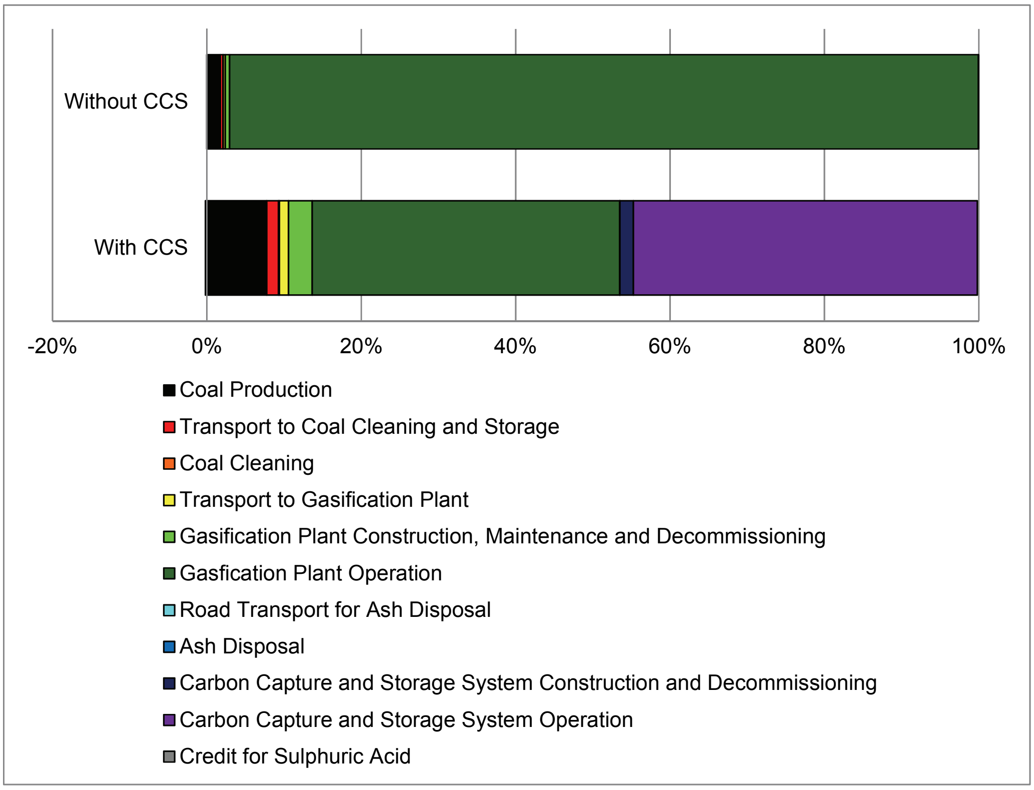


Figure 32 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Brown Coal by Gasification; Default Values and Consequential LCA Methodology



The main sources of GHG emissions associated with H_2 production from wind power by electrolysis are the generation of electricity for drying, in the case with no salt cavern storage and the generation of electricity for compression and drying, in the case with salt cavern storage (see Figures 33 and 34). Significant contributions to total GHG emissions arise from the manufacture of wind turbines under the consequential LCA methodology.

Figure 33 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Wind Power by Electrolysis; Default Values and RED Methodology

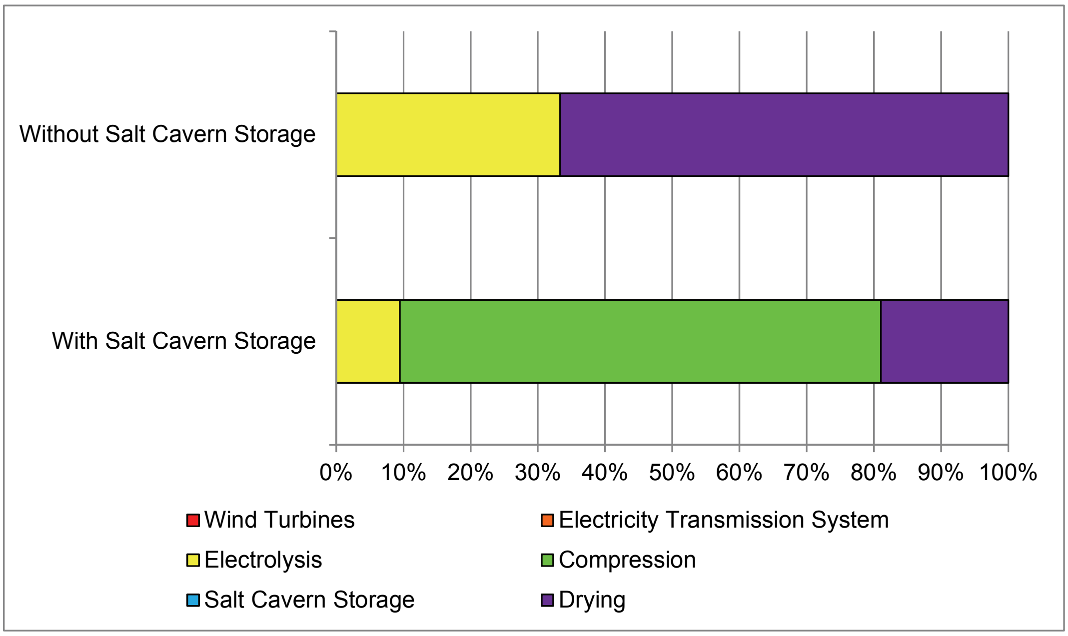
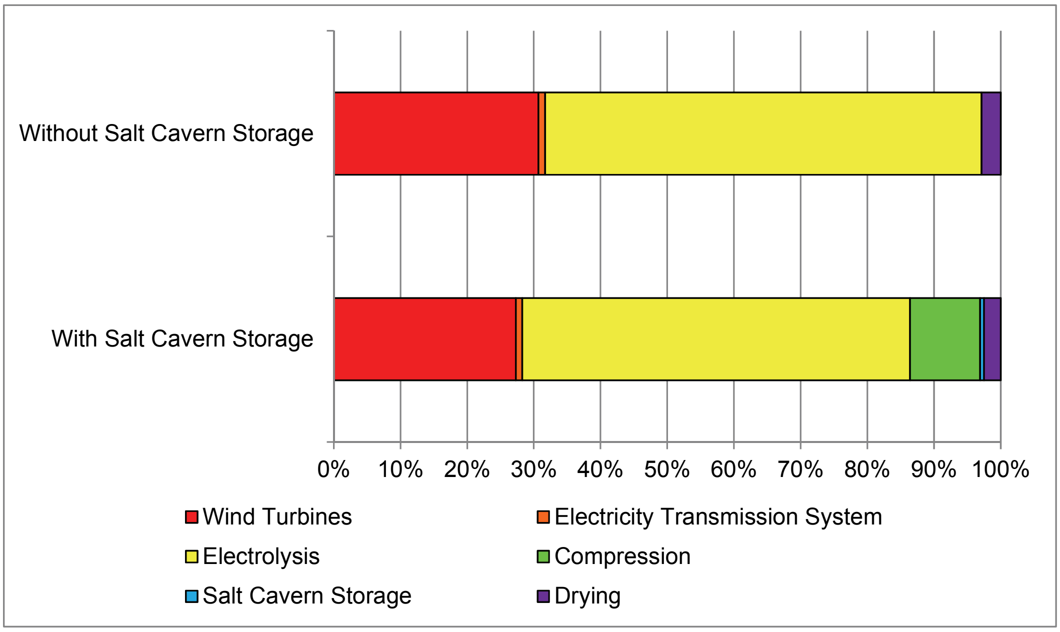


Figure 34 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Wind Power by Electrolysis; Default Values and Consequential LCA Methodology



With application of the RED methodology, the only contribution to total GHG emissions for H_2 production from solar power by electrolysis is the provision of water for electrolysis (see Figure 35). In contrast, the predominant contribution to total GHG emissions for H_2 production from solar power by electrolysis is the manufacture and construction of the solar power tower when the consequential LCA methodology is applied (see Figure 36). This is due to the energy intensive materials used in solar power tower manufacture and the relatively low productivity of this particular means of producing H_2.

Figure 35 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Solar Power by Electrolysis; Default Values and RED Methodology

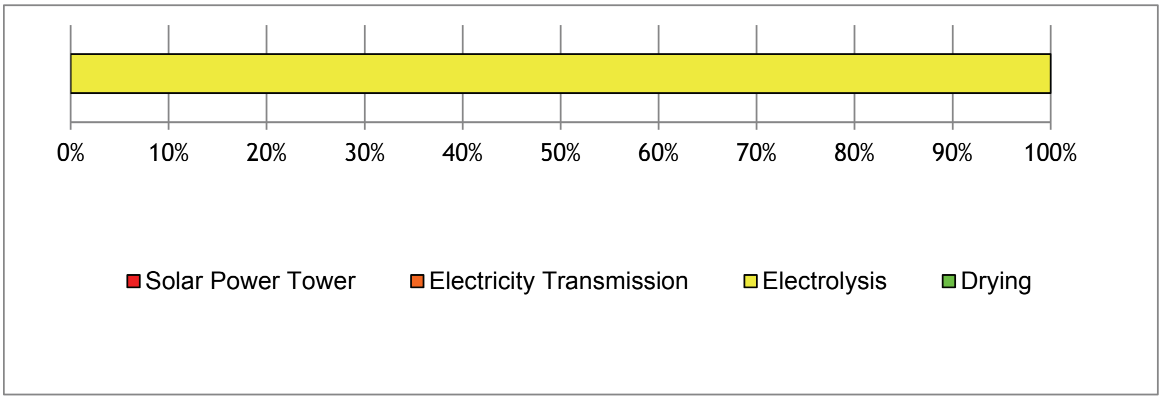
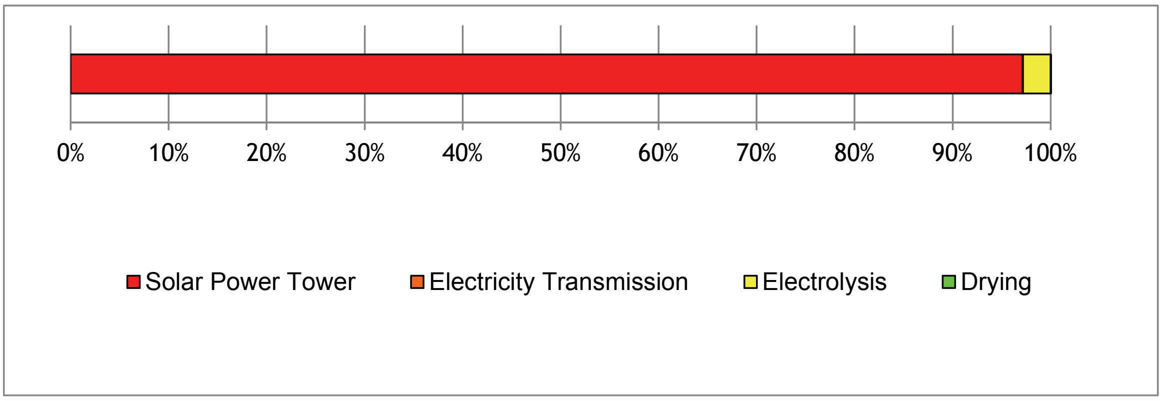


Figure 36 Contributions to Total Greenhouse Gas Emissions for Hydrogen Production from Solar Power by Electrolysis; Default Values and Consequential LCA Methodology



A sample of results illustrating the sensitivities of total GHG emissions to selected parameters for H_2 production is provided in Figures 37 to 42. The total GHG emissions for H_2 production from natural gas by steam reforming only vary slightly with the distance over which the feedstock is carried (see Figures 37 and 38). Variations of total GHG emissions inputs to H_2 production from brown coal by gasification are more sensitive to the distance that the coal is shipped (see Figures 39 and 40). This is due mainly to the relatively lower energy density of coal as a feedstock. The total GHG emissions to H_2 production from wind power by electrolysis are markedly sensitive to the load factor of the offshore wind turbines (see Figure 41). Similar sensitivity is seen in the variation of total GHG emissions to H_2 production from solar power with electrolysis against the level of insolation available to solar power towers (see Figure 42).

Figure 37 Variation of Total Greenhouse Gas Emissions for Hydrogen Production from Natural Gas by Steam Reforming with Transport Distance by Pipeline and LNG Shipping; RED Methodology

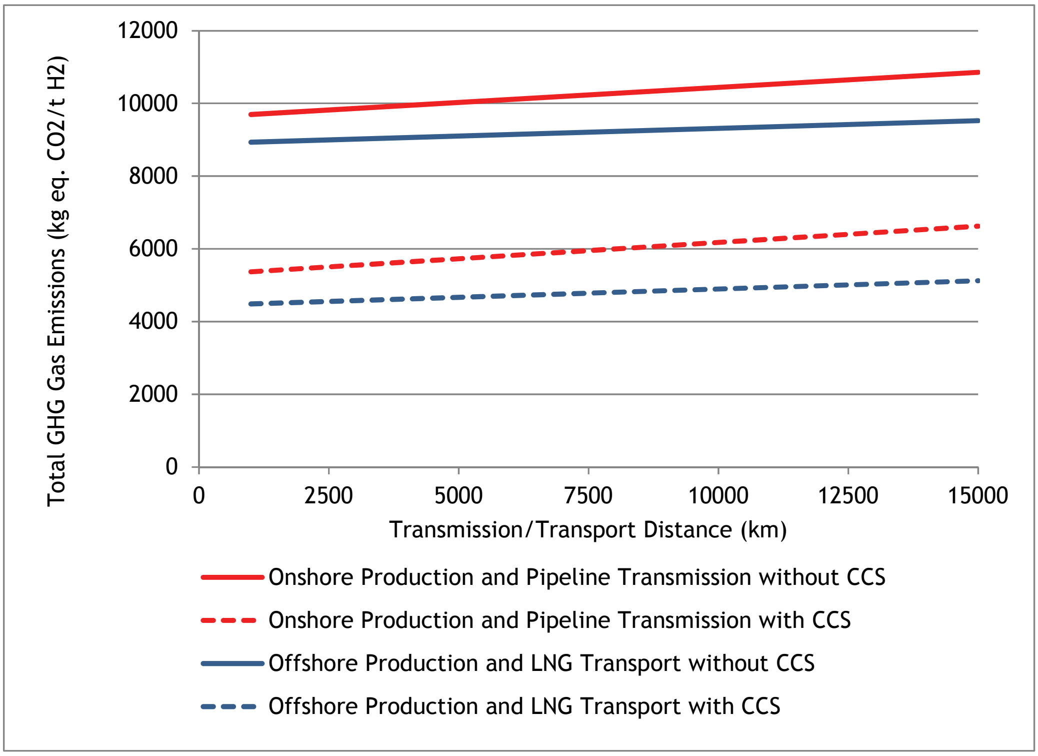


Figure 38 Variation of Total Greenhouse Gas Emissions for Hydrogen Production from Natural Gas by Steam Reforming with Transport Distance by Pipeline and LNG Shipping; Consequential LCA Methodology

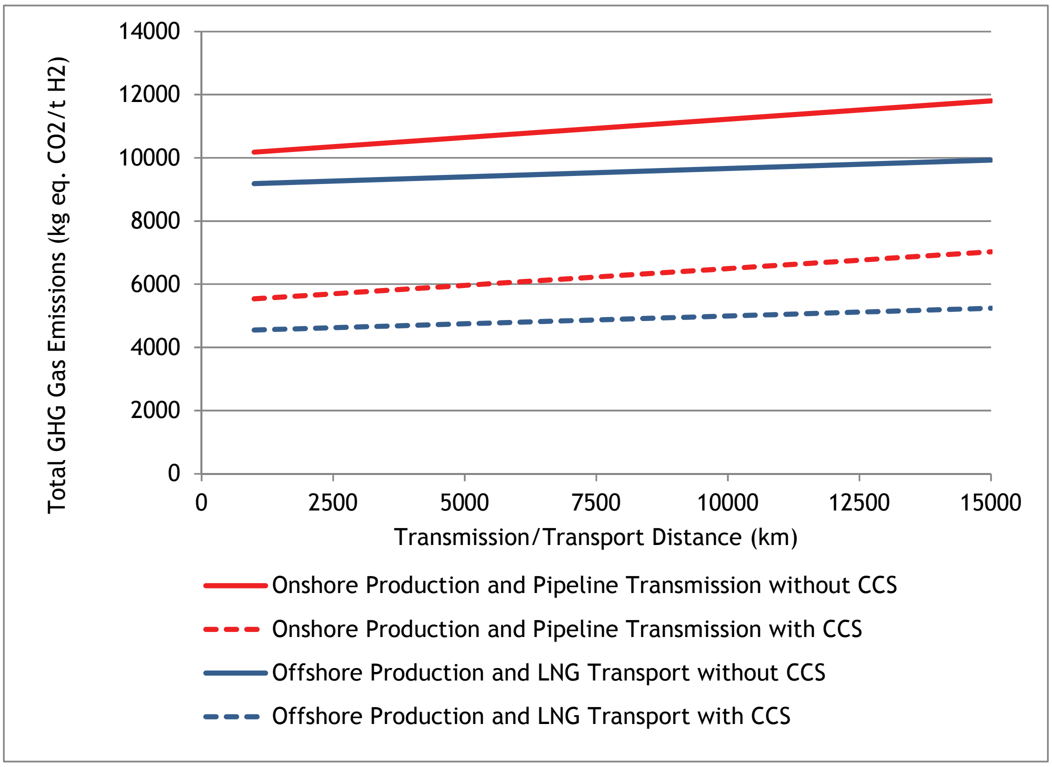


Figure 39 Variation of Total Greenhouse gas Emissions for Hydrogen Production from Brown Coal by Gasification with Shipping Round Trip Distance; RED Methodology

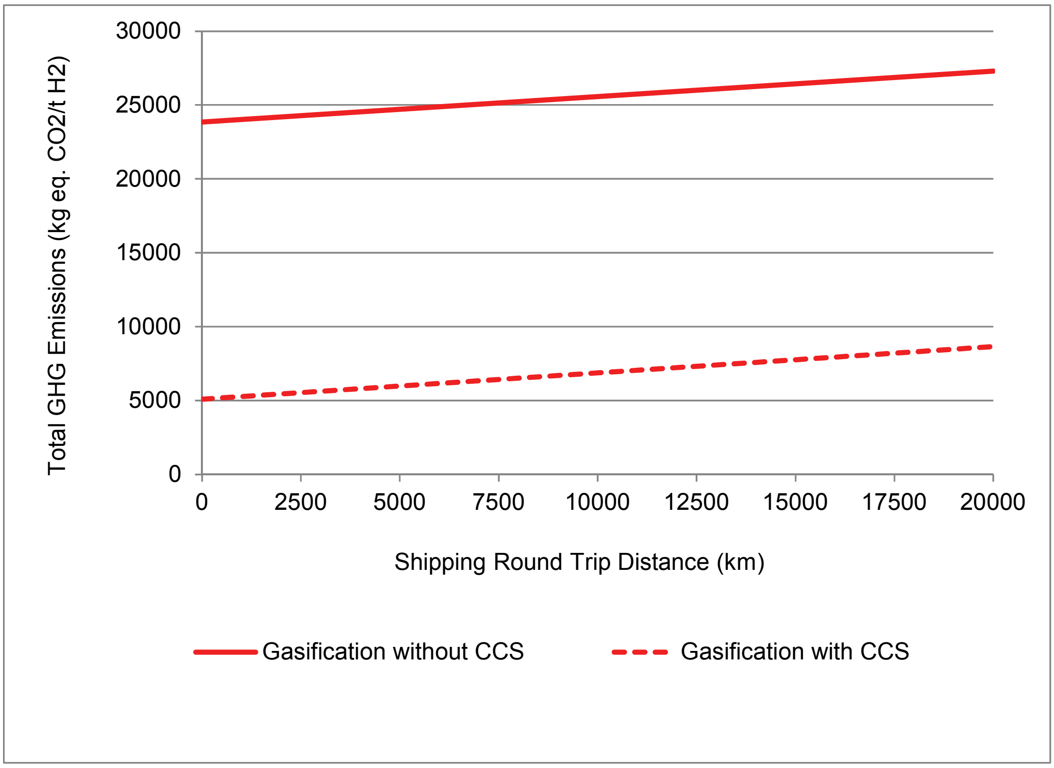


Figure 40 Variation of Total Greenhouse gas Emissions for Hydrogen Production from Brown Coal by Gasification with Shipping Round Trip Distance; Consequential LCA Methodology

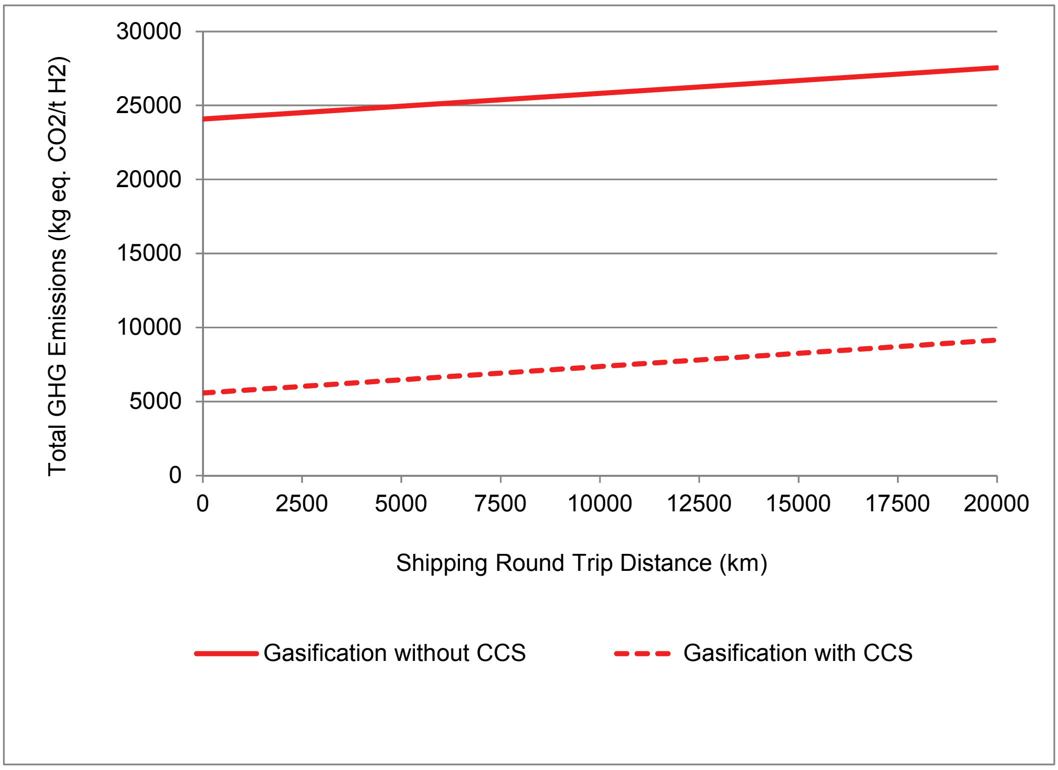


Figure 41 Variation of Total Greenhouse Gas Emissions for Hydrogen Production from Wind Power by Electrolysis with Load Factor; Consequential LCA Methodology

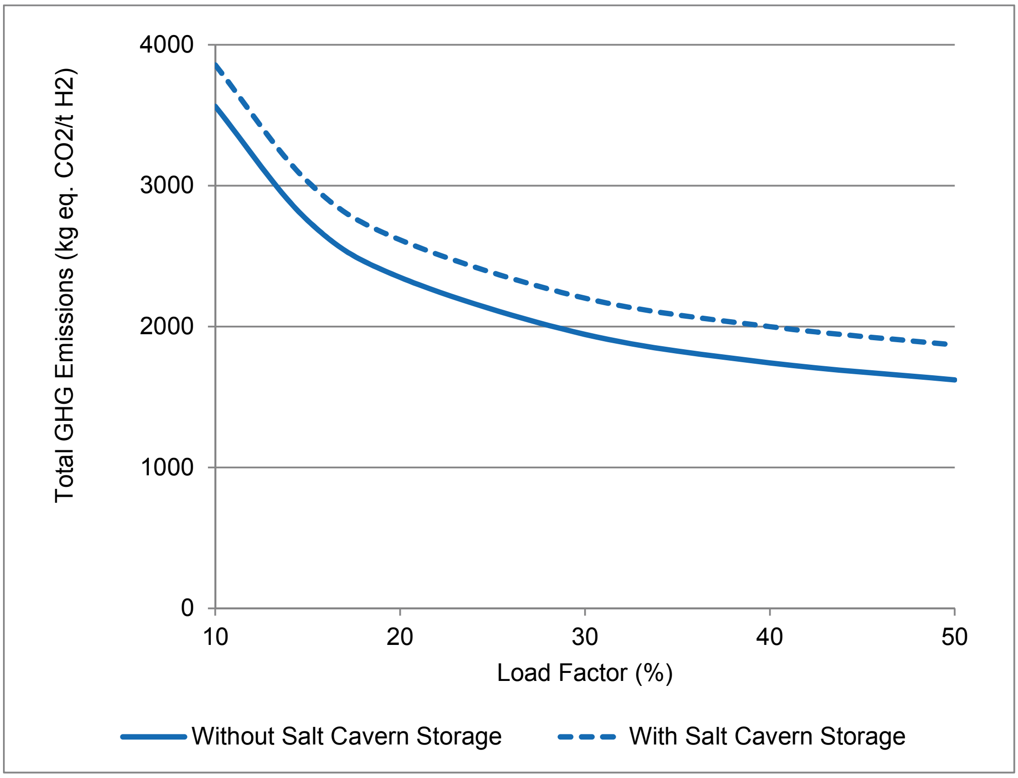
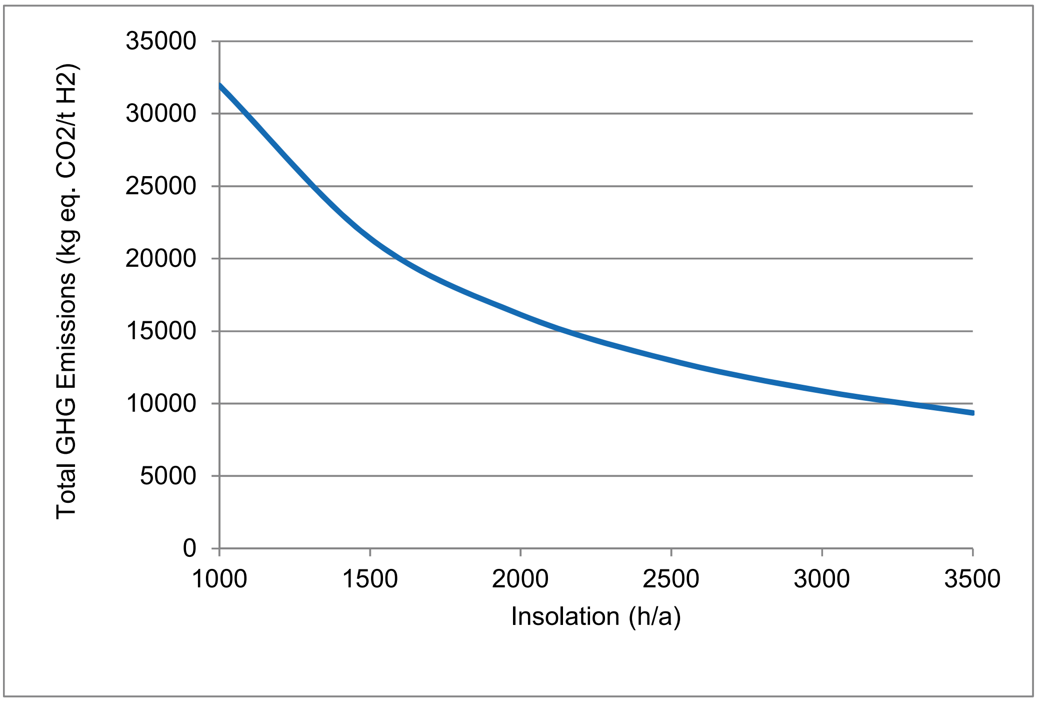


Figure 42 Variation of Total Greenhouse Gas Emissions for Hydrogen Production from Solar Power by Electrolysis with Insolation; Consequential LCA Methodology



Assuming only road transport for hydrogen delivery to refuelling stations and using other default values in the relevant workbooks, the average estimates of total GHG emissions for LH_2 and GH_2 delivery and refuelling, derived with the RED and consequential LCA methodologies, are summarised in Table 13. These results adopt a value of 100 km for the round trip distance for delivery and, where relevant, the total GHG emissions factor for EU-27 grid electricity in 2009. As noted previously, the results for LH_2 and GH_2 delivery in Table 13 cannot be compared directly since liquefaction is not taken into account in the former case.

Table 13 Total Greenhouse Gas Emissions for Hydrogen Delivery and Refuelling: Default Values for 100 Kilometre Round Trip Distance by Road Only

Pathway	Total Greenhouse Gas Emissions (kg eq. CO_2/t H_2)	
	RED Methodology	Consequential LCA Methodology
LH_2 Delivery and Refuelling	287	892
Compressed H_2 Delivery and Refuelling:		
- Steel Tube Trailer Delivery for Cars	1,258	1,735
- Steel Tube Trailer Delivery for Buses	1,173	1,624
- Composite Tube Trailer Delivery for Cars	1,070	1,782
- Composite Tube Trailer Delivery for Buses	1,019	1,715

Relative contributions to total GHG emissions for LH_2 delivery and refuelling are shown in Figures 43 and 44, and to GH_2 delivery and refuelling in Figures 45 and 46. It can be seen that the contribution from the refuelling station dominates total GHG emissions for LH_2 delivery and refuelling (see Figures 43 and 44). In contrast, compression makes a significant additional contribution to the total GHG emissions for GH_2 delivery and refuelling (see Figures 45 and 46). The relative contributions of road transport are lower for composite tube trailers than those for steel tube trailers. This is because more compressed GH_2 can be carried in composite tube trailers than in steel tube trailers.

Figure 43 Contributions to Total Greenhouse Gas Emissions for Liquid Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip Distance by Road Only and RED Methodology

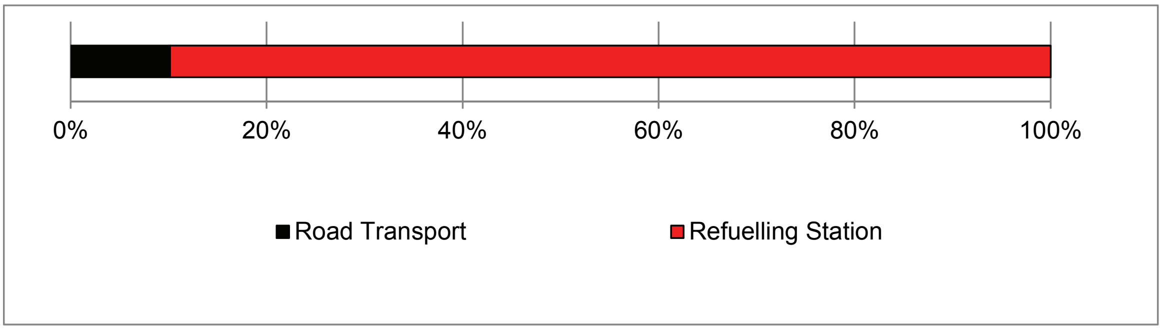


Figure 44 Contributions to Total Greenhouse Gas Emissions for Liquid Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip Distance by Road Only and Consequential LCA Methodology

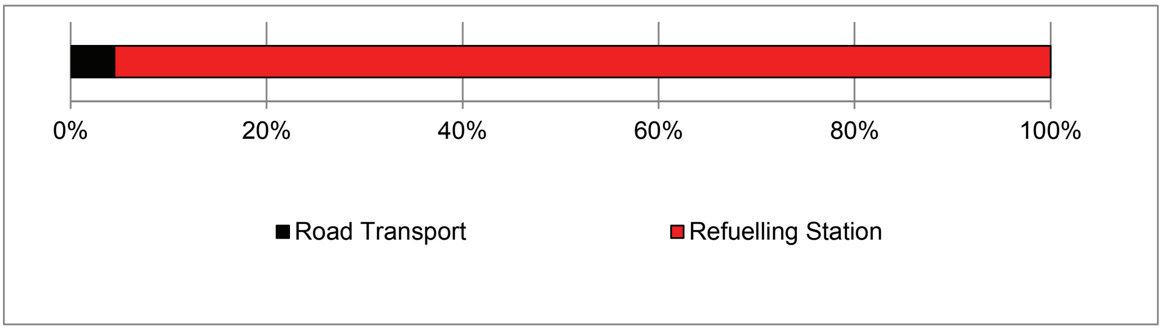


Figure 45 Contributions to Total Greenhouse Gas Emissions for Compressed Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip and RED Methodology

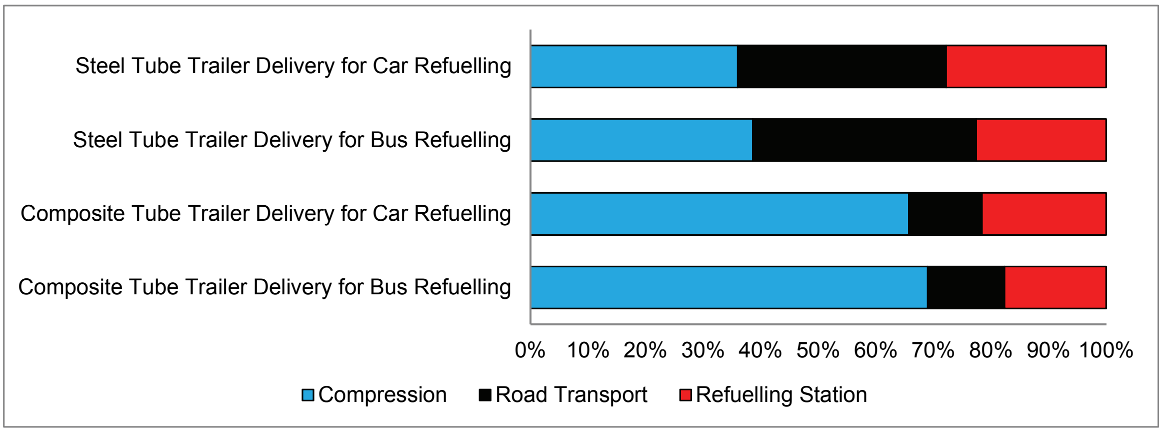
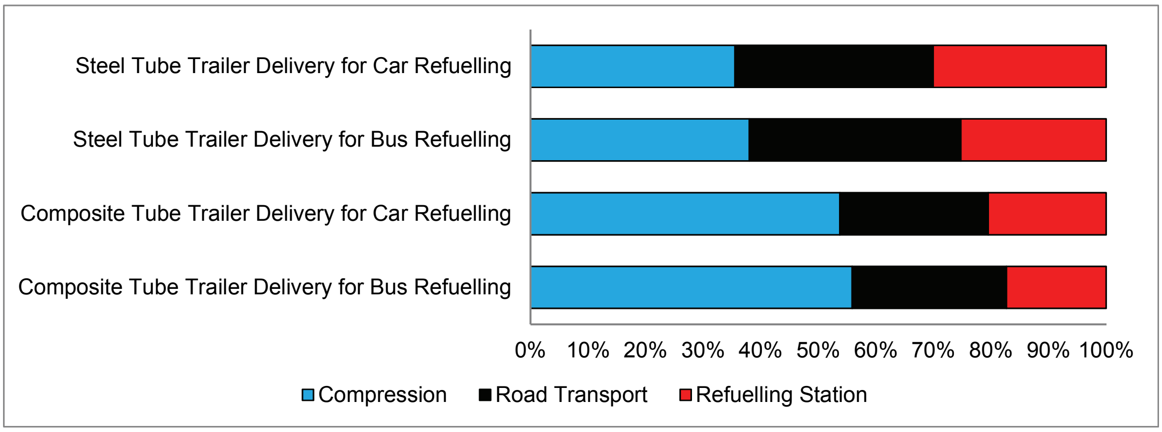


Figure 46 Contributions to Total Greenhouse Gas Emissions for Compressed Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip and Consequential LCA Methodology



A sample of results illustrating the sensitivities of total GHG emissions to the round trip delivery distance for LH_2 and GH_2 is provided in Figures 47 to 50. Total GHG emissions for LH_2 delivery and refuelling are moderately sensitive to this distance (see Figures 47 and 48). However, this effect is more pronounced for GH_2 delivery and refuelling (see

Figures 49 and 50). Differences in total GHG emissions for GH_2 delivery by steel tube trailers and composite tube trailers are also demonstrated. In particular, it will be noted that for round trip delivery distances greater than between 20 and 60 km, the use of composite tube trailers has lower total primary energy inputs than those of steel tube trailers.

Figure 47 Variation of Total Greenhouse Gas Emissions for Liquid Hydrogen Delivery and Refuelling with Round Trip Distance; Road Only Delivery and RED Methodology

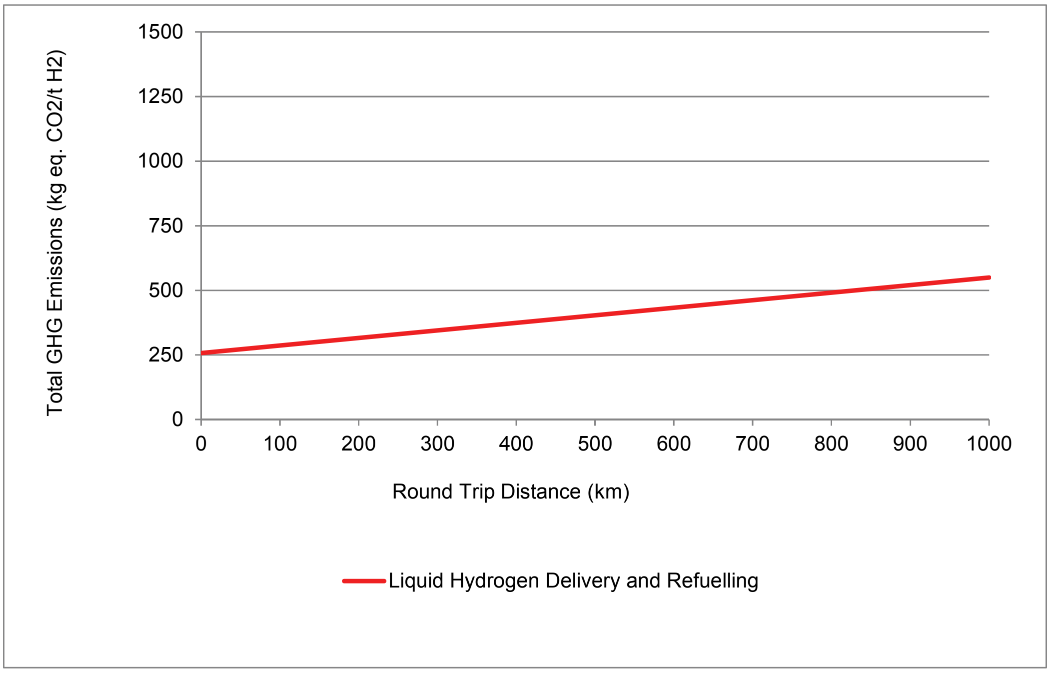


Figure 48 Variation of Total Greenhouse Gas Emissions for Liquid Hydrogen Delivery and Refuelling with Round Trip Distance; Road Only Delivery and Consequential LCA Methodology

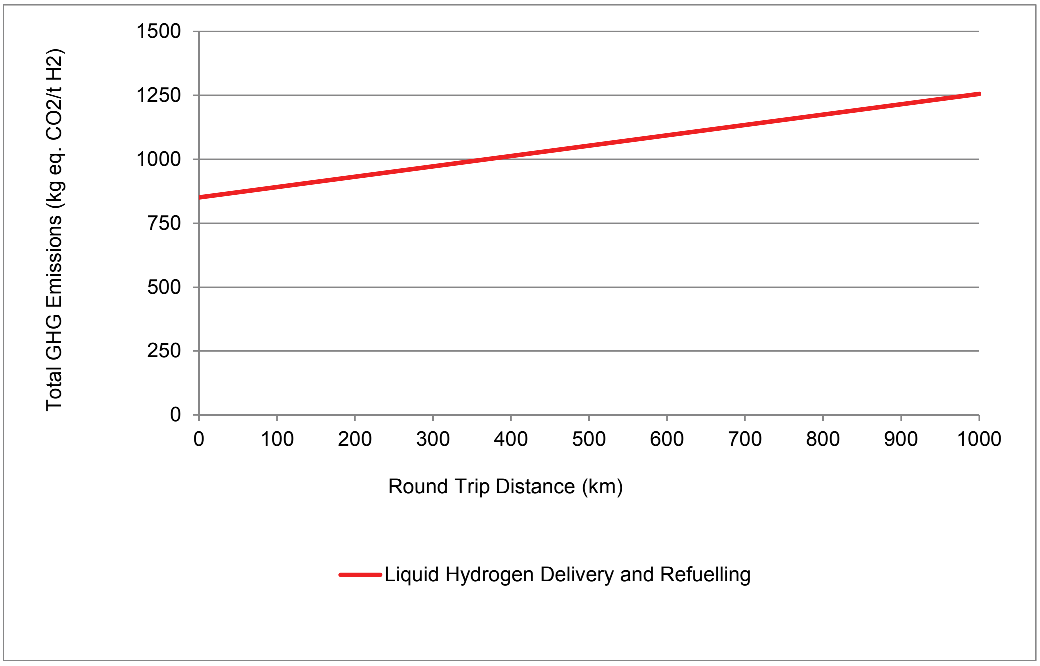


Figure 49 Variation of Total Greenhouse Gas Emissions for Compressed Hydrogen Delivery and Refuelling with Round Trip Distance; RED Methodology

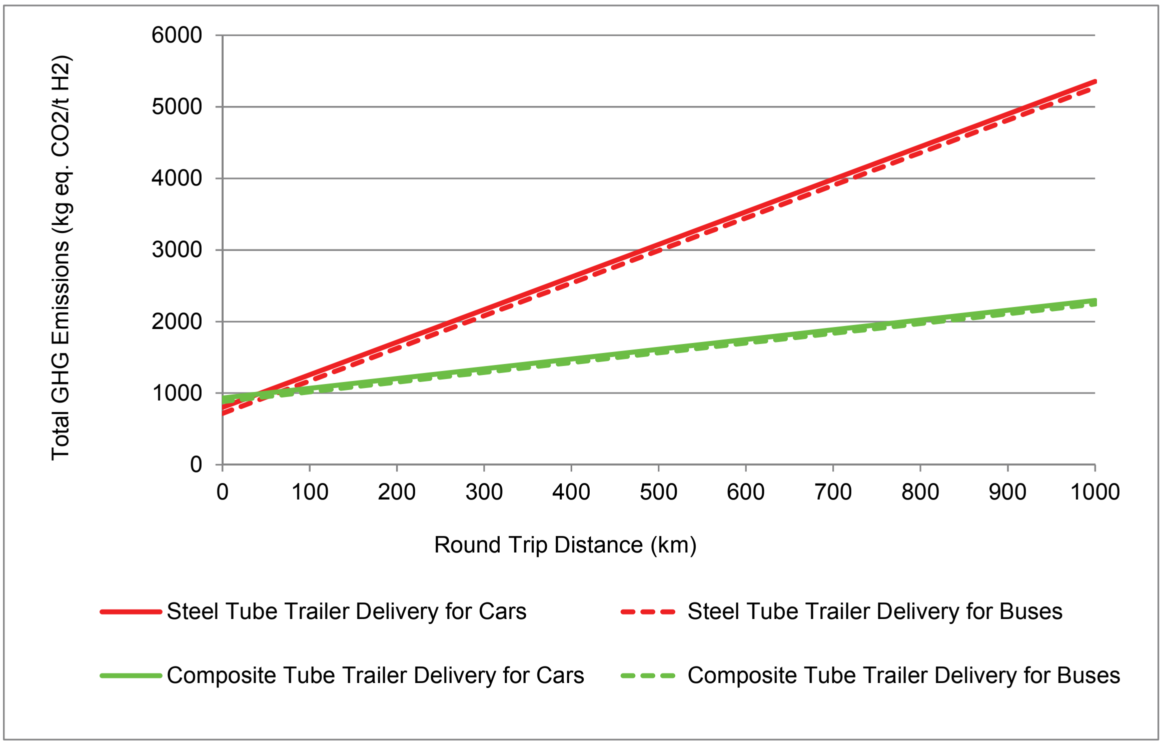
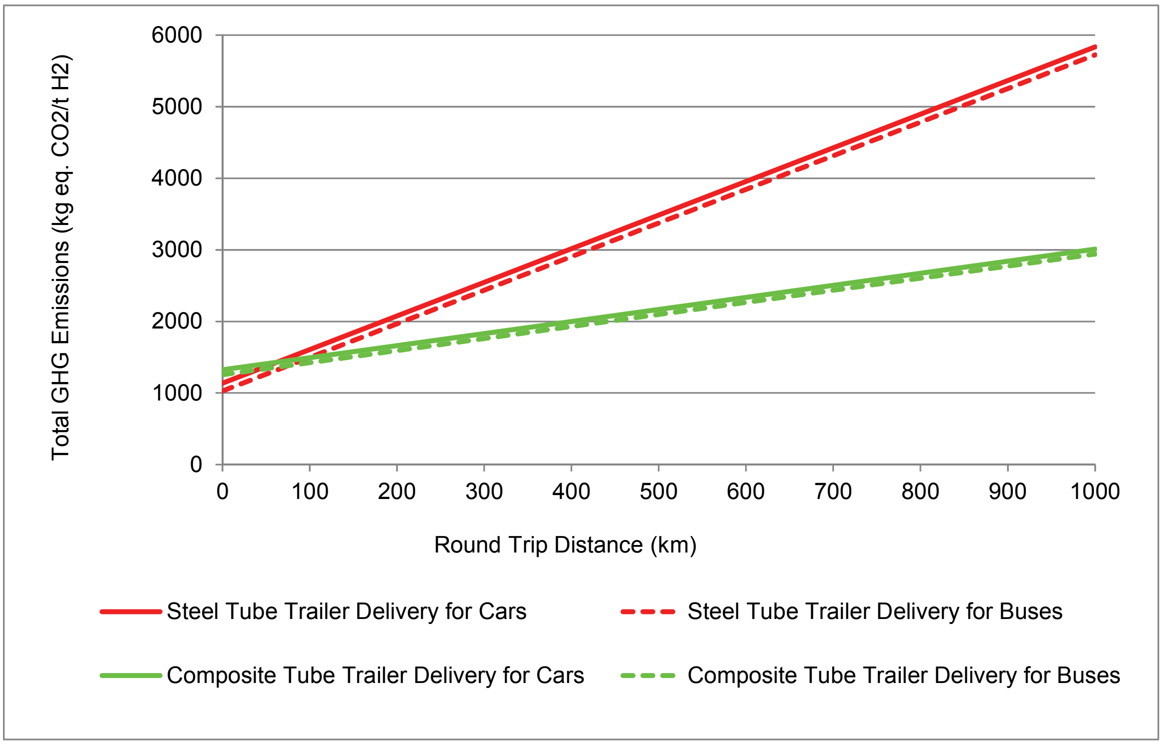


Figure 50 Variation of Total Greenhouse Gas Emissions for Compressed Hydrogen Delivery and Refuelling with Round Trip Distance; Consequential LCA Methodology



With the default values adopted in the IDEALHY – Hydrogen Utilisation v04.xlxs workbook, estimates of the total GHG emissions for the manufacture, maintenance and decommissioning of a fuel cell car and bus are summarised in Table 14. These results are based on consequential LCA methodology only because contributions from vehicle manufacture, maintenance and decommissioning are not included with the RED methodology.

Table 14 Total Greenhouse Gas Emissions for Hydrogen Utilisation; Default Values and Consequential LCA Methodology

Pathway	Total Greenhouse Gas Emissions (kg eq. CO_2/km)
Fuel Cell Car	0.0777
Fuel Cell Bus	0.6970

4.3 Internal Economic Costs

Using the default values adopted in the appropriate workbooks, the average estimates and ranges of total internal economic costs, in € 2012, for the production of H_2 from relevant sources by specified technologies are summarised in Table 15.

Table 15 Total Internal Economic Costs for Hydrogen Production: Default Values

Pathway	Total Internal Economic Costs (€ 2012/t H_2)
H_2 from Natural Gas by Steam Reforming:	
- without CCS	1,574 ± 48
- with CCS	1,684 ± 48
H_2 from Brown Coal by Gasification:	
- without CCS	1,325 ± 303
- with CCS	2,207 ± 332
H_2 from Wind Power by Electrolysis:	
- without salt cavern storage	3,098 ± 322
- with salt cavern storage	3,275 ± 340
H_2 from Solar Power by Electrolysis	6,499 ± 2,469

The relative contributions to total internal economic costs for H_2 production from natural gas by steam reforming, from brown coal by gasification, and from wind power and solar power by electrolysis, based on default values, are shown in Figures 51 to 54, respectively. The largest contribution to total internal economic costs for H_2 production from natural gas by steam reforming are due to the original production of the feedstock regardless of whether CCS is adopted (see Figure 51). In the case of H_2 production from brown coal by gasification without CCS, the largest contributions to total internal costs are surface mining and gasifier construction and maintenance (see Figure 52). For H_2 production from brown coal by gasification with CCS, the most prominent contributions are surface mining, gasifier construction and maintenance, and CCS operation (see also Figure 52). The dominant contributions to total internal economic costs for H_2 production from wind power by electrolysis are the costs of wind turbine and electrolyser manufacture, regardless of whether salt cavern storage is used (see Figure 53). The predominant contribution to total internal economic costs of H_2 production from solar power by electrolysis is the costs of solar power tower manufacture (see Figure 54).

Figure 51 Contributions to Total Internal Economic Costs for Hydrogen Production from Natural Gas by Steam Reforming; Default Values

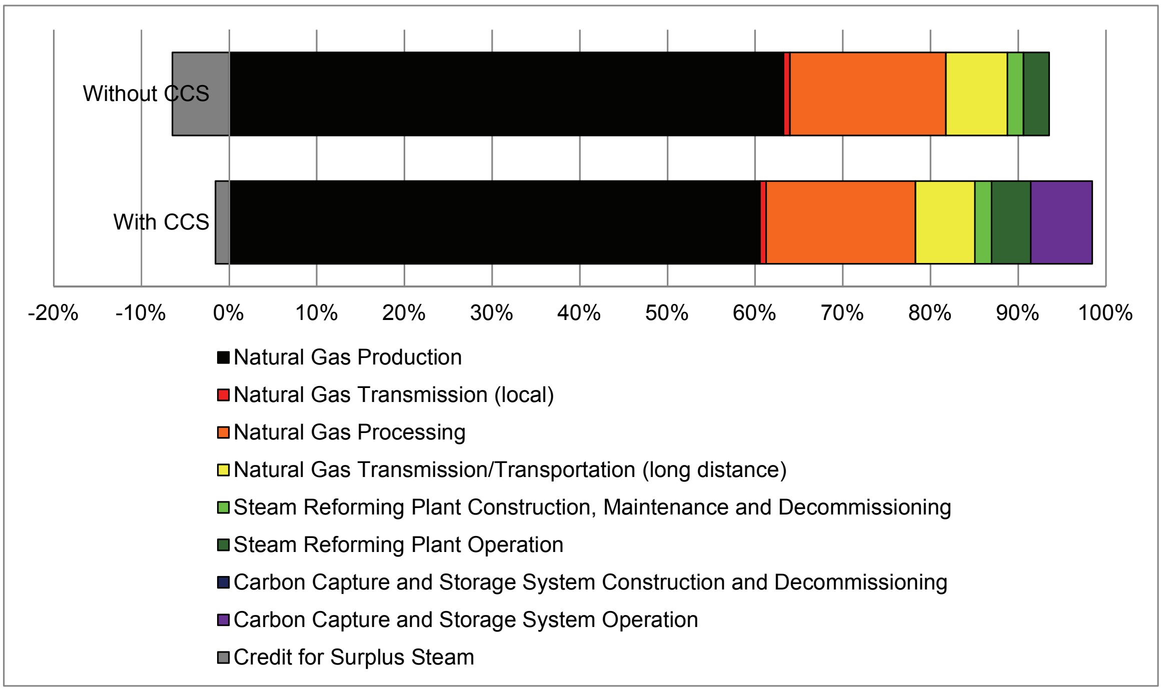


Figure 52 Contributions to Total Internal Economic Costs for Hydrogen Production from Brown Coal by Gasification; Default Values

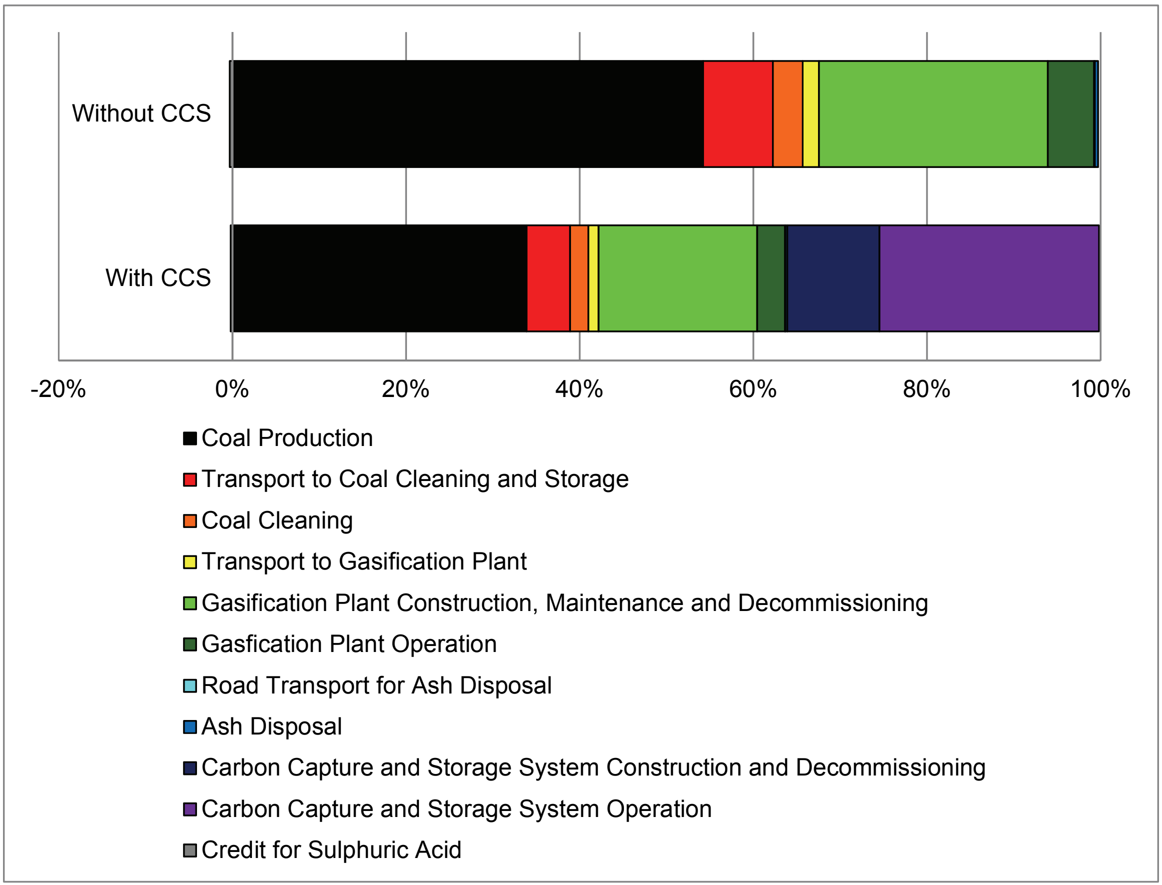


Figure 53 Contributions to Total Internal Economic Costs for Hydrogen Production from Wind Power by Electrolysis; Default Values

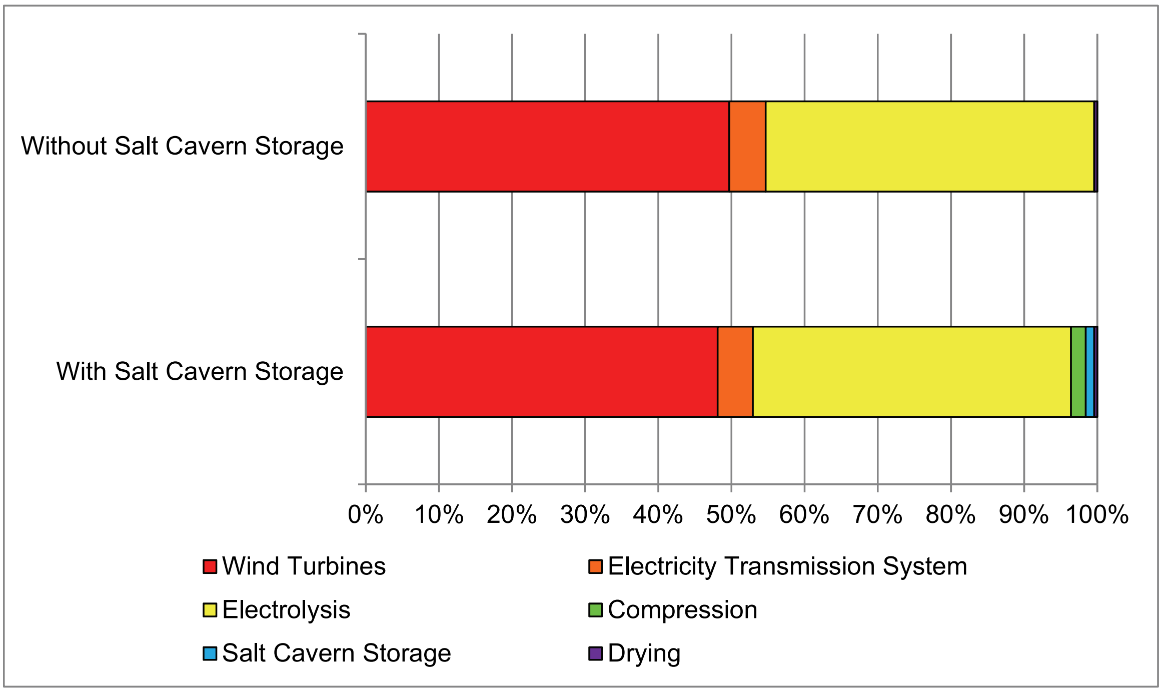
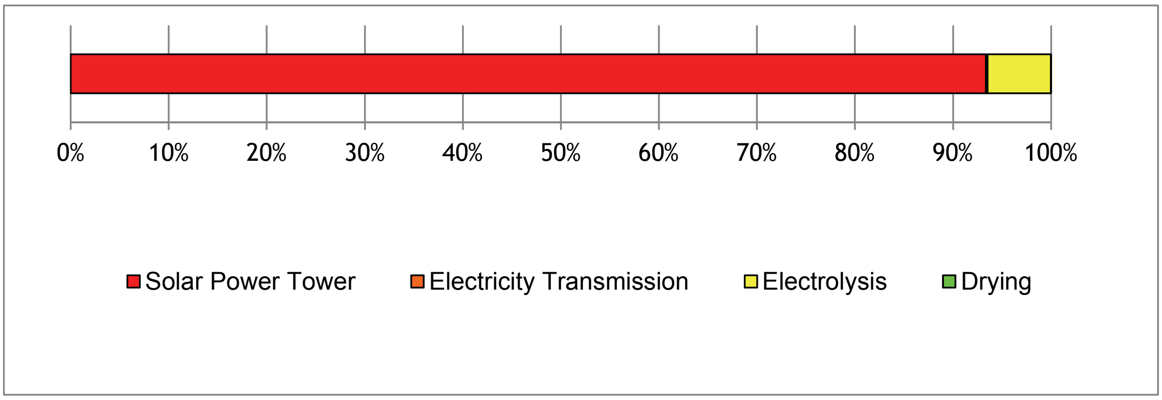


Figure 54 Contributions to Total Internal Economic Costs for Hydrogen Production from Solar Power by Electrolysis; Default Values



A sample of results illustrating the sensitivities of total internal economic costs to selected parameters for H_2 production is provided in Figures 55 to 58. The total internal economic costs for H_2 production from natural gas by steam reforming only vary slightly with the distance over which the feedstock is carried (see Figure 55). Variations of total internal economic costs of H_2 production from brown coal by gasification are markedly more sensitive to the distance that the coal is shipped (see Figure 56). The total internal economic costs of H_2 production from wind power by electrolysis are very sensitive to the load factor of the offshore wind turbines (see Figure 57). Similar sensitivity is seen in the variation of total internal economic costs of H_2 production from solar power with electrolysis against the level of insolation available to solar power towers (see Figure 58).

Figure 55 Variation of Total Internal Economic Costs for Hydrogen Production from Natural Gas by Steam Reforming with Transport Distance by Pipeline and LNG Shipping

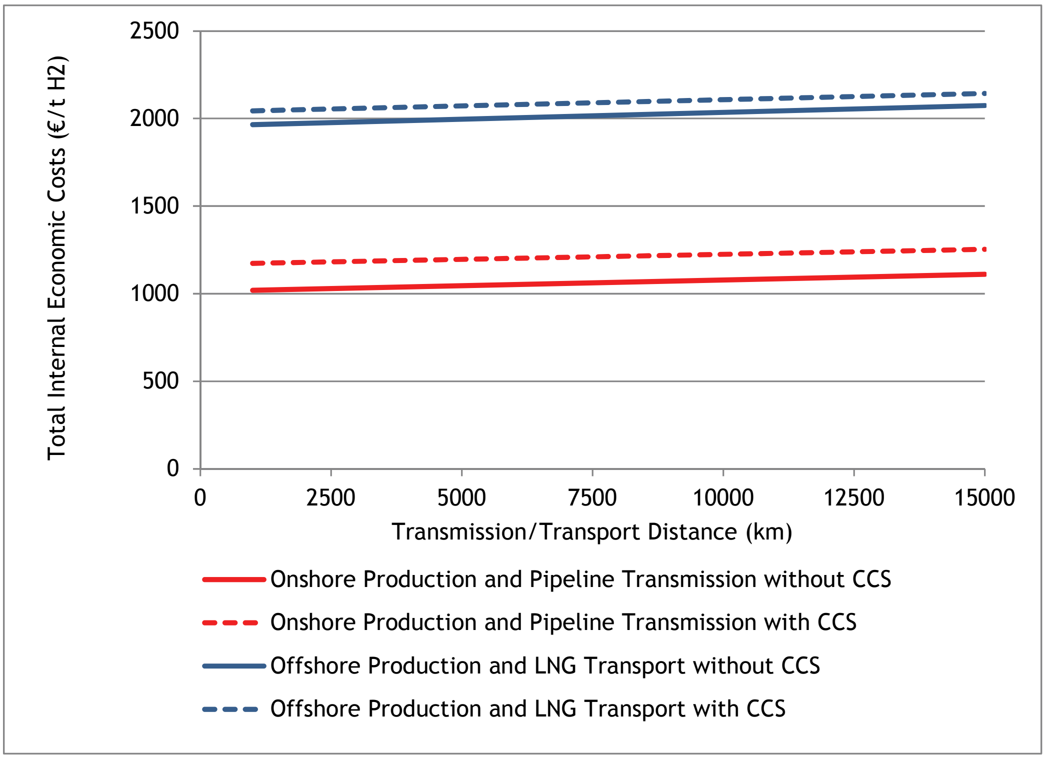


Figure 56 Variation of Total Internal Economic Costs for Hydrogen Production from Brown Coal by Gasification with Shipping Round Trip Distance

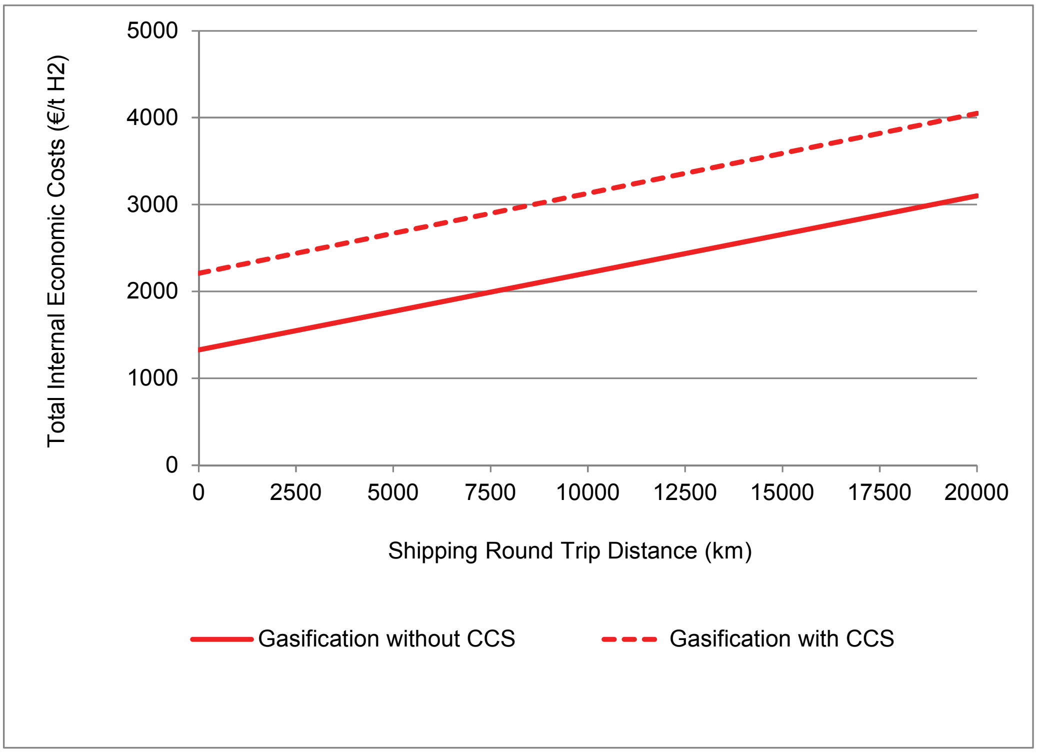


Figure 57 Variation of Total Internal Economic Costs for Hydrogen Production from Wind Power by Electrolysis with Load Factor

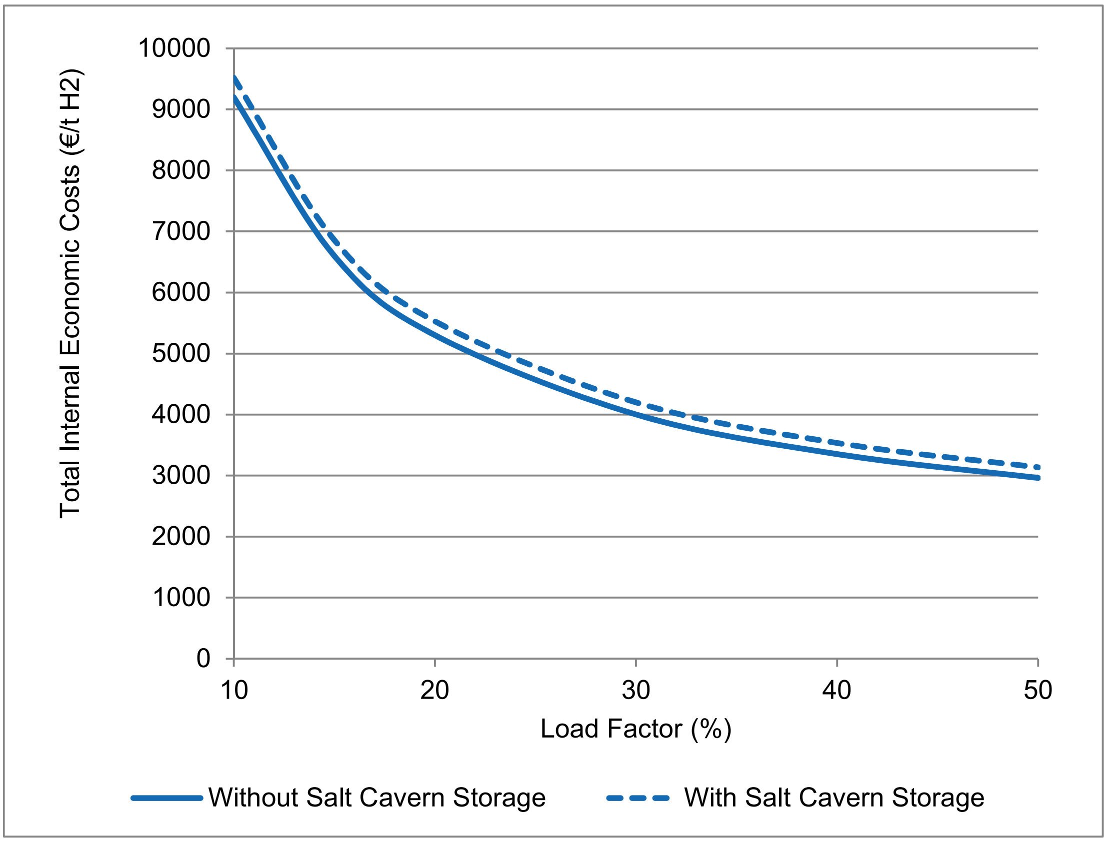
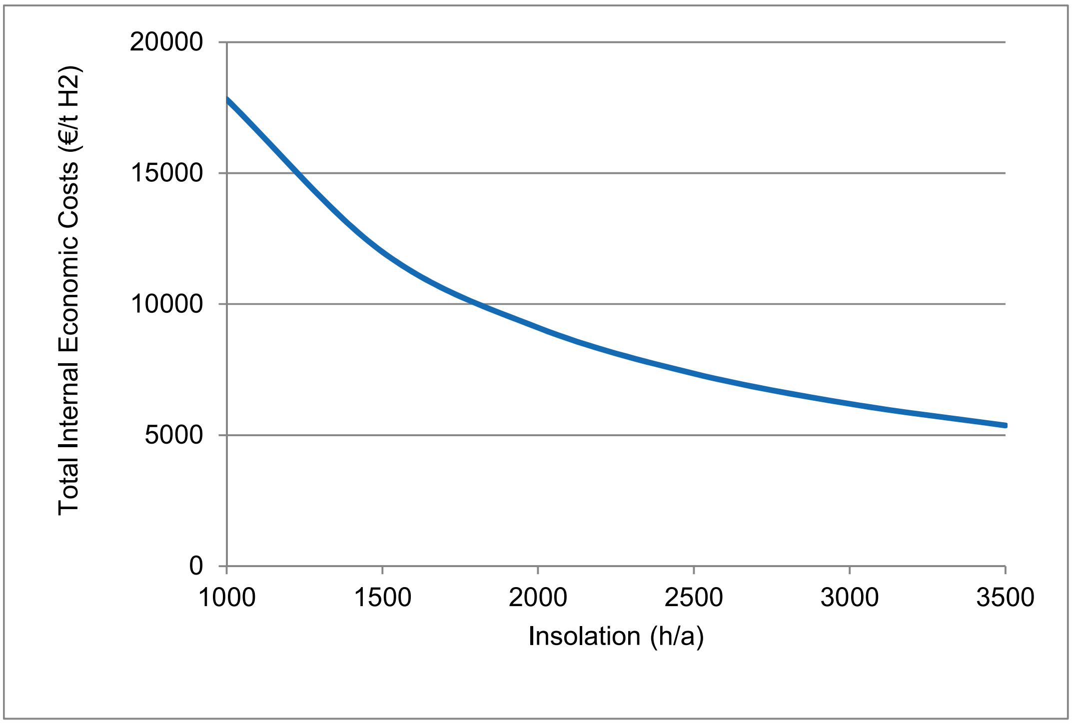


Figure 58 Variation of Total Internal Economic Costs for Hydrogen Production from Solar Power by Electrolysis with Insolation



Assuming only road transport for hydrogen delivery to refuelling stations and using other default values in the relevant workbooks, the average estimates of total internal economic costs, in € 2012, for LH_2 and GH_2 delivery and refuelling are summarised in Table 16. These results adopt a value of 100 km for the round trip distance. As pointed out before, the results for LH_2 and GH_2 delivery in Table 16 cannot be compared directly since liquefaction is not taken into account in the former case.

Table 16 Total Internal Economic Costs for Hydrogen Delivery and Refuelling: Default Values for 100 Kilometre Round Trip Distance by Road Only

Pathway	Total Internal Economic Costs (€ 2012/t H_2)
LH_2 Delivery and Refuelling	1,607
Compressed H_2 Delivery and Refuelling:	
- Steel Tube Trailer Delivery for Cars	2,156
- Steel Tube Trailer Delivery for Buses	2,128
- Composite Tube Trailer Delivery for Cars	1,996
- Composite Tube Trailer Delivery for Buses	1,980

Relative contributions to total internal economic costs for LH_2 delivery and refuelling are shown in Figure 59, and to GH_2 delivery and refuelling in Figure 60. The costs of the refuelling station dominate the total internal economic costs of LH_2 delivery and refuelling (see Figure 59), whilst the costs of road transport and the refuelling station are the main contributions to the total internal economic costs of compressed GH_2 delivery and refuelling (see Figure 60). Relatively low H_2 supply rates assumed in refuelling stations have a significant role in these outcomes.

Figure 59 Contributions to Total Internal Economic Costs for Liquid Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip Distance by Road Only

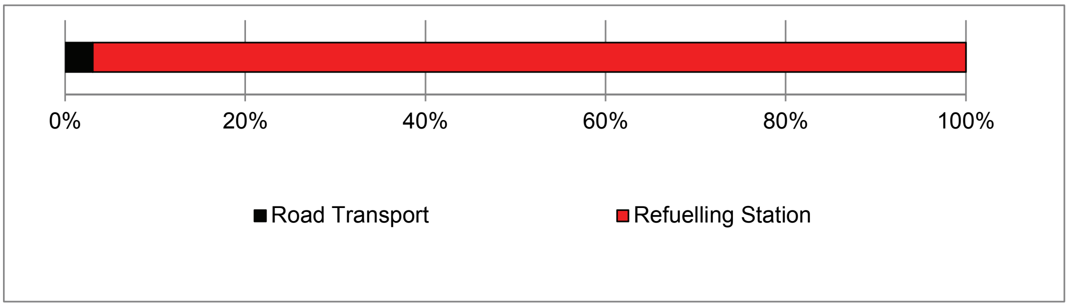
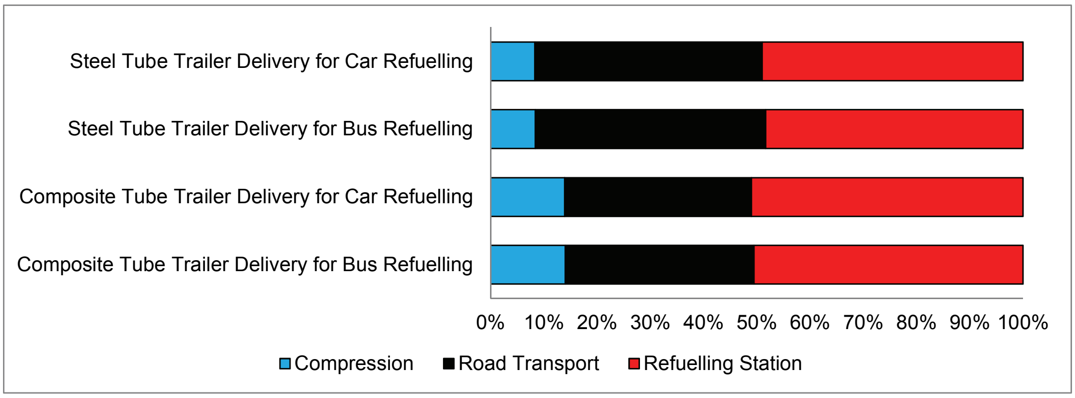


Figure 60 Contributions to Total Internal Economic Costs for Compressed Hydrogen Delivery and Refuelling; 100 Kilometre Round Trip



A sample of results illustrating the sensitivities of total internal economic costs to the round trip delivery distance for LH_2 and GH_2 is provided in Figures 61 and 62, respectively. Whilst the total internal economic costs for LH_2 delivery and refuelling are moderately sensitive to this distance (see Figure 61), the effect is more pronounced for GH_2 delivery and refuelling (see Figure 62). It will be noted that, in almost all instances, the use of composite tube trailers is more economic than steel tube trailers for GH_2 transportation.

Figure 61 Variation of Total Internal Economic Costs for Liquid Hydrogen Delivery and Refuelling with Round Trip Distance; Road Only Delivery

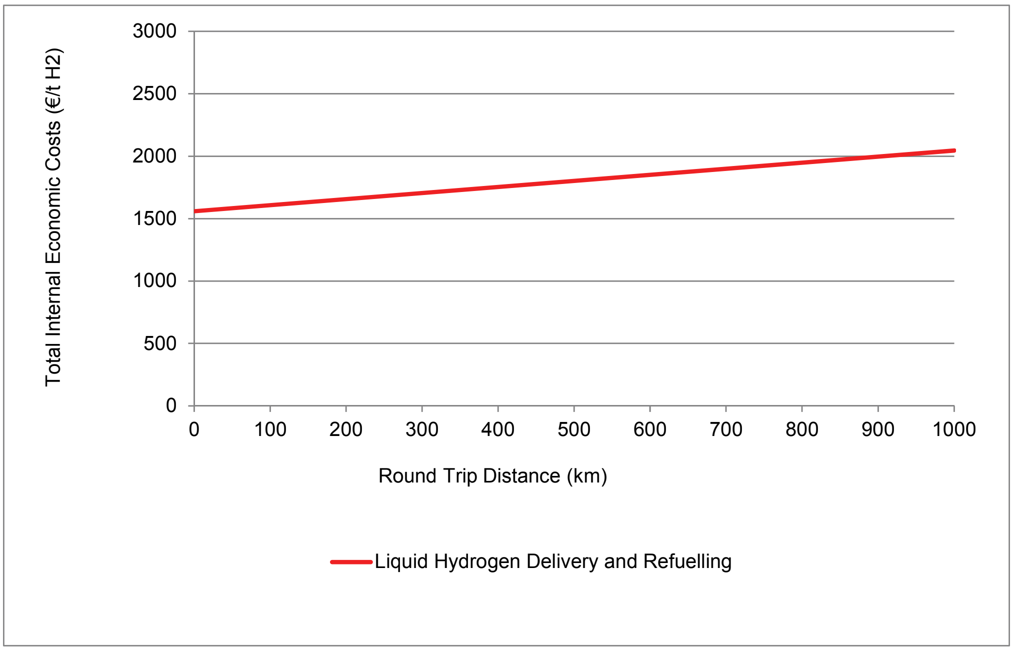


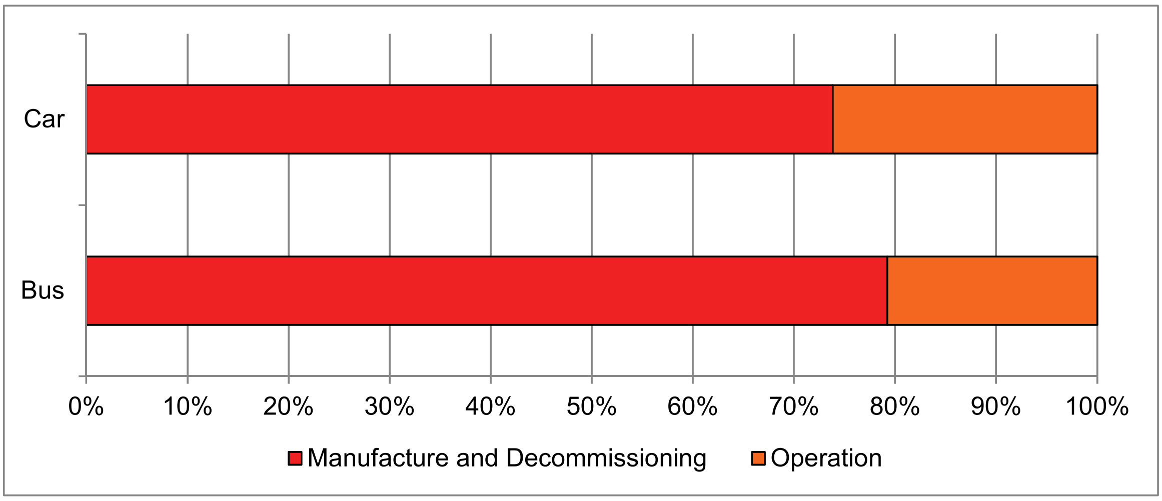
Figure 62 Variation of Total Internal Economic Costs for Compressed Hydrogen Delivery and Refuelling with Round Trip Distance

Based on the default values adopted in the IDEALHY – Hydrogen Utilisation v04.xlxs workbook, estimates of the total internal economic costs for the manufacture, maintenance, decommissioning and operation of a fuel cell car and bus, in € 2012, are summarised in Table 17. The larger contribution to the total internal economic costs of H_2 utilisation is vehicle manufacture, as shown in Figure 63. It should be noted that the operation costs of the fuel cell car mainly consists of maintenance, whilst the operation costs of the fuel cell bus includes the costs of the driver as well as maintenance.

Table 17 Total Internal Economic Costs for Hydrogen Utilisation

Pathway	Total Internal Economic Costs (€/km)
Fuel Cell Car	0.194
Fuel Cell Bus	3.530

Figure 63 Contributions to Total Internal Economic Costs for Hydrogen Utilisation: Default Values



5. Conclusions

The MS Excel workbooks developed in the IDEALHY Project enable calculation of total primary energy inputs (as an indicator of energy resource depletion), CO_2, CH_4, N_2O and total GHG emissions (as indicators of global climate change), and total internal economic costs (in € 2012 values as approximations across the EU) for the production of H_2 from natural gas by steam reforming, from brown coal by gasification and from wind power and solar power by electrolysis, for delivery of LH_2 and compressed GH_2 for refuelling, and for the utilisation of H_2 in fuel cell cars and buses. These MS Excel workbooks incorporate significant functionality to address the effects of a very wide range of technical parameters. Additionally, the MS Excel workbooks also incorporate the RED and consequential LCA methodologies particular for the evaluation of total GHG emissions in the context of regulatory requirements and policy analysis, respectively. The main features of the MS Excel workbooks have been summarised and illustrative results have been presented which demonstrate their functionality. This is important as these MS Excel workbooks will be used in conjunction with those for advanced H_2 liquefaction, developed later in the IDEALHY Project, in the overall assessment of alternative pathways for the provision of H_2 to fuel cell vehicles which will be reported subsequently in Deliverable D3.17.

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