Environmental Impact Study of BIG HIT

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BIG HIT: Building Innovative Green Hydrogen Systems in an Isolated Territory: a Pilot for Europe

Environmental Impact Study of BIG HIT

A report into the environmental impact of the project

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List of Abbreviations

ANM ---- Active Network Management

CAL ---- Calvera Maquinaria S.L

CES ---- Community Energy Scotland

DTU ---- Technical University of Denmark

EMEC ---- European Marine Energy Centre

ERE ---- Eday Renewable Energy

FHA ---- Foundation for the Development of New Hydrogen Technologies

FiT ---- Feed in Tariff

GIA ---- Giacomini

HRS ---- Hydrogen Refuelling Station

LCA ---- Life Cycle Assessment

LCC ---- Life Cycle Cost

OHT ---- Orkney Hydrogen Trading

OIC ---- Orkney Islands Council

PEM ---- Polymer Electrolyte Membrane

ROC ---- Renewables Obligation scheme

SDT ---- Shapinsay Development Trust

SHFCA ---- Scottish Hydrogen and Fuel Cell Association

S-LCA ---- Social Life Cycle Assessment

SMEs ---- Small and Medium Enterprises

SnT ---- Surf 'n' Turf

SYM ---- Symbio FC

1. Executive Summary

The BIG HIT project is creating a replicable hydrogen territory in Orkney (Northern part of Scotland) by implementing a fully integrated model of hydrogen production, storage, transportation and utilised for heat, power and mobility purposes. BIG HIT will absorb curtailed electricity from one wind turbine on the site of Shapinsay and one wind turbine and up to seven tidal test sites on the site of Eday, and use 1.5 MW of Polymer Electrolyte Membrane (PEM) electrolysis to convert water into ~50 t pa of hydrogen. There are three applications of hydrogen: heat, electricity, and mobility. The hydrogen will be used to provide heat to one or two local primary schools. It will be transported by ferry in hydrogen tube trailers to the largest island, Mainland, and the capital city, Kirkwall, where it will be used to fuel a 75 kW cogeneration fuel cell stack, which will provide heat and power to the harbour buildings and 2 ferries when docked. Finally, it will be used at a hydrogen refuelling station to fuel a fleet of 5 fuel cell vans.

The objective is to assess the potential environmental impact of hydrogen production, distribution and energy application in the Orkney Islands. A life cycle assessment (LCA) analysis is conducted on the hydrogen system concept of the BIG HIT project, according to ISO 14040 and ISO 14044. The impact assessment is carried out using 1 kg hydrogen produced and consumed as the functional unit. The life cycle stage of BIG HIT project includes hydrogen production, hydrogen distribution, hydrogen application, and the replaced energy. The system boundary is built based on BIG HIT mass flow, considering the system expansion with 'no BIG HIT' as the substituted energy supply in the analysis. Fourteen impact categories are assessed including climate change. The impact method is ILCD 2011 midpoint, where ILCD is the International Reference Life Cycle Data System. The software used is SimaPro.

For the Orkney Islands, the analysis show that the hydrogen applications will contribute to avoid emissions from electricity not coming from RES, oil and diesel. The total impact on climate change for electricity production from hydrogen is estimated to be 1.62 kg CO_2 eq per kg hydrogen consumed. It can replace the climate change impact of 3.82 kg CO_2 eq from UK average low voltage electricity. The system of hydrogen for heat includes electrolysis unit, hydrogen boiler and transport (road transport). The substituted energy is oil, which is currently being used for heating supply. The total climate change impact for the hydrogen for heat is estimated to be 1.61 kg CO_2 eq per kg hydrogen consumed, which can replace 9.45 kg CO_2 eq of carbon emissions from burning oil. The system of hydrogen for mobility includes electrolysis unit, hybrid vehicle manufacture (vehicle manufacture, fuel cell battery, electric battery), transport (both road and ferry transport). The substituted energy in the transport application is diesel. Compared to diesel vehicles, the impacts from hydrogen application of hybrid vehicle is negative regarding climate change, acidification and water resource depletion. The total climate change for mobility is 4.36 kg CO_2 eq per kg hydrogen consumed, which can replace 8.39 kg CO_2 eq from carbon emissions from using fossil fuels.

The quantitative assessment of other impact categories, according to the ILCD method, suggests that no significant trade-offs with other impact categories can be found. Climate change represent a good indicator for other impacts as well.

The impact results show that most emissions occur at the hydrogen production stage. The contribution to climate change stemming from the hydrogen production corresponds to more than 80% of the total impacts with regards to the electricity application, 98% with regards to the heat application and 38% regarding the mobility application.

The detail life cycle assessment of the hydrogen production has shown that the largest environmental impact can be attributed to the manufacturing of the PEM electrolyser system. Therefore, a detailed life cycle assessment of the 1 MW of electrolyser system has been conducted separately to elaborate on the environmental impacts. The results show that the electrolysis stacks are responsible for the largest part of the environmental impact due to the material input of platinum, stainless steel, etc. However, the amount of metals used as catalysts is only roughly estimated. For the current study a mix of recycled and virgin materials have been modelled; this is based on the current norms for the materials modelled, for example, steel, a percentage of recycled materials has been included, based on the global average of recycled crap steel. Any recycling of catalyst materials has not been included in the study due to lack of information regarding the recycling process.

Based on the current assessment of hydrogen production and energy applications, it is concluded that the system demonstrated in the BIG HIT project will represent a significant reduction of Green House Gas emissions compared to the current energy system. Overall, hydrogen used for electricity generation has the potential to reduce the climate change impact (CO_2 eq) by 58% compared to the conventional energy solution. Likewise, hydrogen used for heat supply reduces the climate change impact by 83%, and hydrogen used for mobility purpose reduces the climate change impact by 48%.

2. Introduction

2.1 Location of the Project

Due to concerns about climate change, renewable energy technologies are growing rapidly and becoming mature. They can provide a major share of electricity demand globally. However, as their market share grows, concerns about potential impacts on the stability and operation of the electricity grid may create barriers to their future expansion. Green hydrogen can be seen as one of the solution for the high percentage of renewables in the energy system. At present, the green hydrogen market is growing and prices are on the way of reaching economies of scale, but are not yet there. Now it is the time to integrate the green hydrogen into the energy system in significant quantities. The experience gained from large-scale demonstration can be used for relevant hydrogen concepts in the future.

The Orkney Islands are located in the Northern Isles of Scotland, situated off the north coast of Great Britain and 16 kilometres north of the coast of Caithness (Fig. 1). The Orkney Islands containing 20 inhabited islands with a total population of 21000, have approx. 66 MW of renewable energy generation (11 MW of wave and tidal turbine, 5 MW micro generation, and 50 MW of wind turbine). In the Orkney Islands, the power connection to the Scottish mainland is at its capacity limit (not all the time), resulting in the archipelago having many of the features of an isolated grid including significant difficulties balancing electricity supply and demand. The possible generation is greater than the local demand, which means that the excess electricity from renewable sources will need to be exported to the Scottish mainland via 2 undersea cables (Fig. 1).

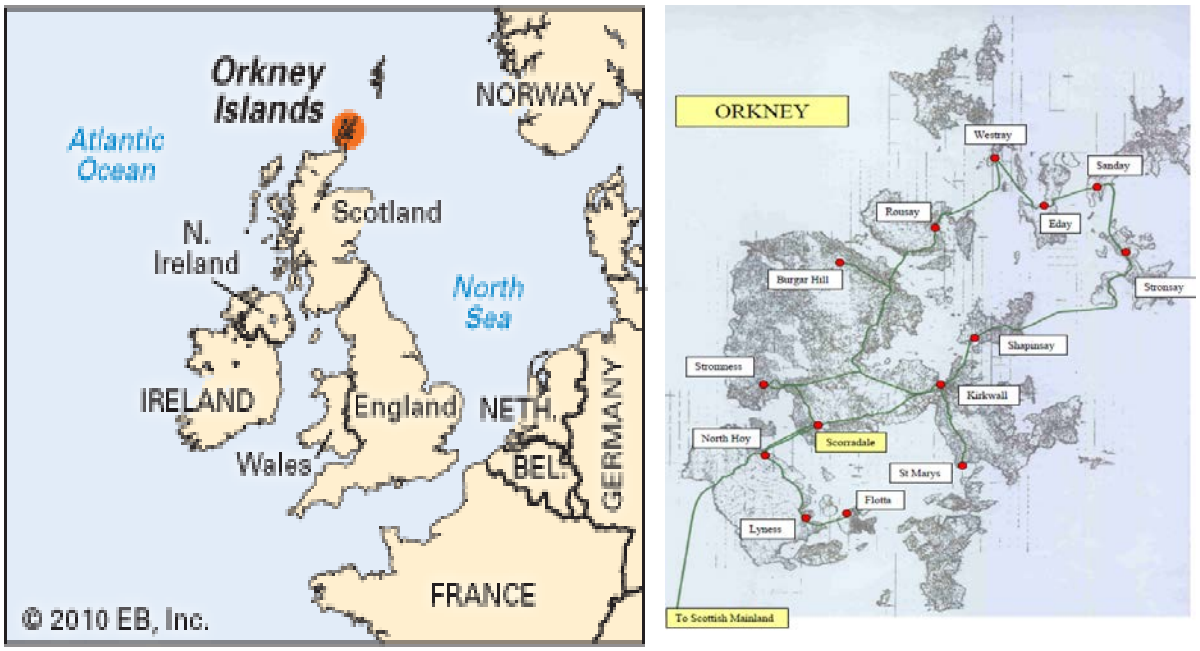

Figure 1 The location of the Orkney islands and the current power cable connections

The Orkney Islands Council (OIC) has set out a hydrogen strategy for overcoming these problems. This recommends using electrolysis as a controllable load on curtailed generators. While this will not prevent completely the Active Network Management (ANM)system from curtailing and preventing export to the grid, it will allow the turbine operators to still receive revenues (e.g. FIT (Feed-in tariff) payments) for the electricity produced, when producing hydrogen from electrolysers powered by electricity generated from wind and tide turbines. The produced hydrogen could be used for energy purposes locally or transported to the mainland Scotland in the future.

2.2 Technical Detail of the Project

This otherwise curtailed generation is a zero carbon energy, leading to a low-cost source of energy that can be used to produce green hydrogen. In the BIG HIT project, the installed two electrolysers will absorb curtailed energy from two wind turbines together with similar excess production from tidal turbines from the islands of Shapinsay and Eday. This electricity will be used to convert water into 50 t pa of hydrogen by 1.5 MW of PEM electrolyser capacity. Hydrogen, as an intermediary energy carrier can be used to produce electricity and heat to meet the demand of the local communities of the islands of Orkney, when the electricity demand is higher than electricity generation and replace conventional electricity generation sources. In the BIG HIT project, some of the produced hydrogen will be used to heat two local primary schools (on Eday and Shapinsay); the rest of the hydrogen will be transported to Mainland (Kirkwall) by road and ferry in 5 hydrogen tube trailers. In Kirkwall, hydrogen will also be used to fuel a 75 kW fuel cell unit, which will provide heat and power to the harbour building and 2 ferries when docked, and for a refuelling station with a fleet of 5 fuel cell vans (Fig. 2).

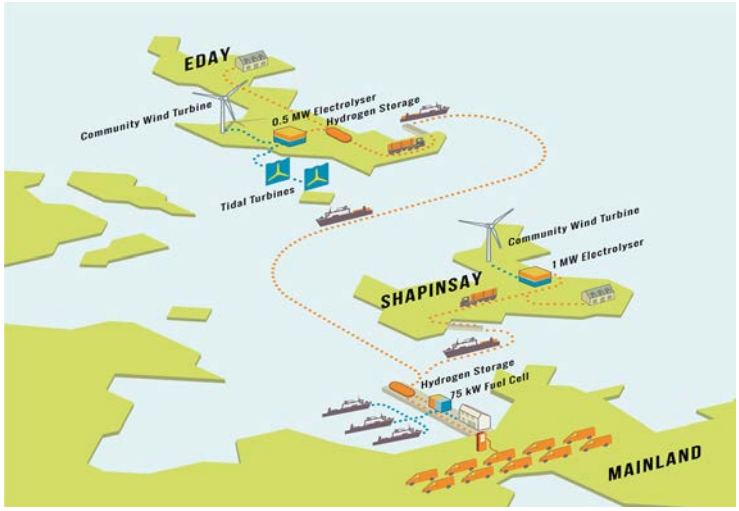

Figure 2 Schematic of BIG HIT project in the Orkney Islands

2.3 Methodological Approach and Structure of Report

Life Cycle Assessment (LCA) methodology is applied to conduct the environmental assessment of the BIG HIT project. In the present report, the LCA is conducted in accordance with the ISO 14040 and 14044 standards (ISO 14044 2006, ISO 14040 2006). Further details about methodological considerations and choices are available in

chapter 3. In the following, the content of each of the sections in the report is briefly described. The task involves the calculation of the energy balance of the hydrogen production, transportation, followed by a detailed life cycle assessment according to ISO 14040 and ISO 14044. The methodology will enable a normalized comparison based on a common functional unit, focusing on not only CO_2 emissions but also other impact categories such as energy resource depletion, human toxicity, respiratory effects etc. Chapter 3 describes the methodology of the study, which is life cycle assessment. Chapter 4 describes the goal and scope of the study and addresses its purpose and the most important methodological choices made in the LCA. Chapter 5 is the life cycle inventory (LCI) phase. Chapter 6 is the life cycle impact assessment phase. Chapter 7 is the life cycle interpretation phase.

3 Methodology

Life Cycle Assessment (LCA) methodology was chosen as the suitable method for the environmental analysis for the project. Taking the whole production chain and spread of activities into consideration, LCA can quantify potential impacts such as contribution to climate change (global warming potential), use of sources depletion (non-renewable energy, renewable, water), ozone depletion, human toxicity, acidification, ecotoxicity, particulate matters, and others. Based on ISO standards, LCA enables analyses of potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (Fig. 3). It also assesses the phases of the life cycle of a product or service that are required during pre-production, production, post-production, transportation and consumption.

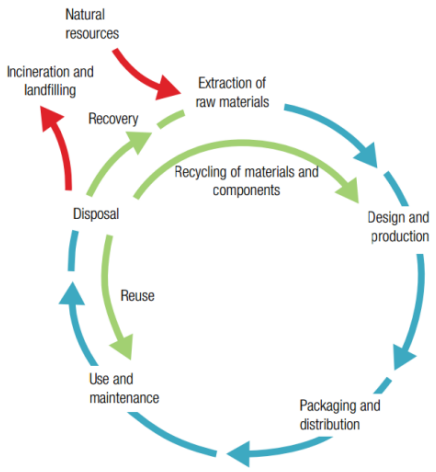

Figure 3 The concept of product life cycle thinking
Source: (UNEP 2007)

The LCA is carried out in accordance with the ISO standards on LCA: ISO 14040 (2006) and ISO 14044 (2006). According to the ISO standards, an LCA consists of four phases: 1. Definition of goal and scope; 2. Life cycle inventory (LCI); 3. Life cycle impact assessment (LCIA); 4. Life cycle interpretation (Fig. 4).

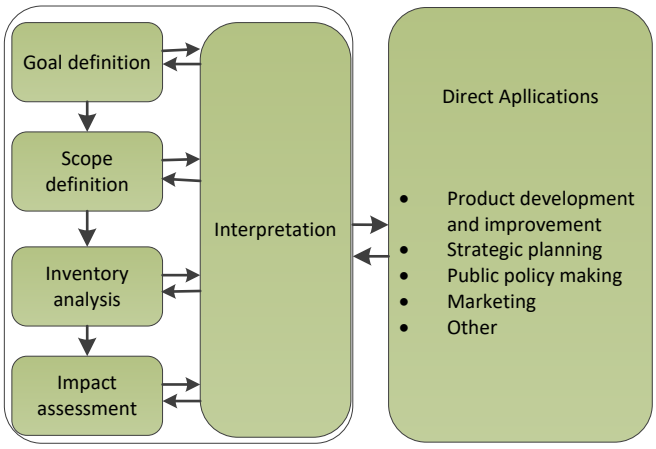

Figure 4 Different phases of LCA methodology based on ISO

There are various methods globally for categorising and characterising the life cycle impact of the flows to and from the environment, which can somewhat complicate the comparability of different LCA studies. Other variables in LCIA include the system boundary (how far upstream, downstream and sidestream does the analysis go), the functional unit (what is the volume/mass/purpose of the object being assessed), and specific LCIA methods such as allocation (how are impacts assigned to the product and by-products, on what basis). In this report, LCA estimates the overall environmental impact from the hydrogen production and applications by given technologies of all the life stages, which include raw materials extraction, transportation, manufacture, use, and disposal. Here, LCA results are used to compare the relative impacts of various fossil-fuel-based of electricity, heat and transport fuels.

4 Goal and Scope

This chapter documents the first phase of the LCA of hydrogen production and application in the Orkney Islands. The goal and scope define the exact questions that the analysis will try to answer, and set its spatial, temporal, and technological boundaries. The goal of the study is to address the potential environmental impacts of the hydrogen production and applications. Traditionally, LCAs are performed as a 'bottom-up' process in which the specific processes in a supply chain are linked. The processes in a product system are linked via physical mass flow or information on market mechanisms (locally or globally). As part of this process, it must be decided which processes will be included, and whether to include aspects such as capital goods, services and possibly some identified less significant inputs of feedstock, ancillaries and energy. The ISO 14044 standard recommends using well-defined cut-off criteria, such as environmental significance. However, in practice, when data is collected there is no need for excluding this data.

4.1 Goal

The main objective of the environmental impact report is to assess the potential environmental impact of the hydrogen production and applications as demonstrated in the BIG HIG project and to predict the environmental performance of the BIG HIT concept through the stages of hydrogen production, transportation and consumption.

The functional unit needs to be defined in this phase. The produced hydrogen will be used to provide electricity and heat to meet the energy demand and as transport fuel for mobility purpose. In the typical LCA analysis, the functional unit of electricity production and transportation is normally not the same. If the functional units are different, we cannot compare the LCIA results of hydrogen applications. In order to compare the different hydrogen applications for energy purposes, the product's function is defined and quantified. The functional unit of hydrogen consumption is calculated based on 1 kg hydrogen consumed for electricity, heat, and mobility purposes.

4.2 System Boundary

When the BIG HIT project is fully implemented, the system's physical boundaries include: electricity generation, PEM electrolyser system, tube trailers for transportation, 75 kW of fuel cell unit, hydrogen refuelling station, and fuel cell vans. Electricity is generated from wind and tidal turbines. One wind turbine is installed in Shapinsay, one wind turbine, and 7 tidal test sites are located on Eday. Both islands of Eday and Shapinsay are located in the northern part of Orkney. The PEM electrolysers on both islands produce hydrogen powered by electricity from wind and tidal turbines in the BIG HIT project. Hydrogen will be used to provide heating to local schools, or be transported to Mainland for electricity and mobility purposes (Fig 5).

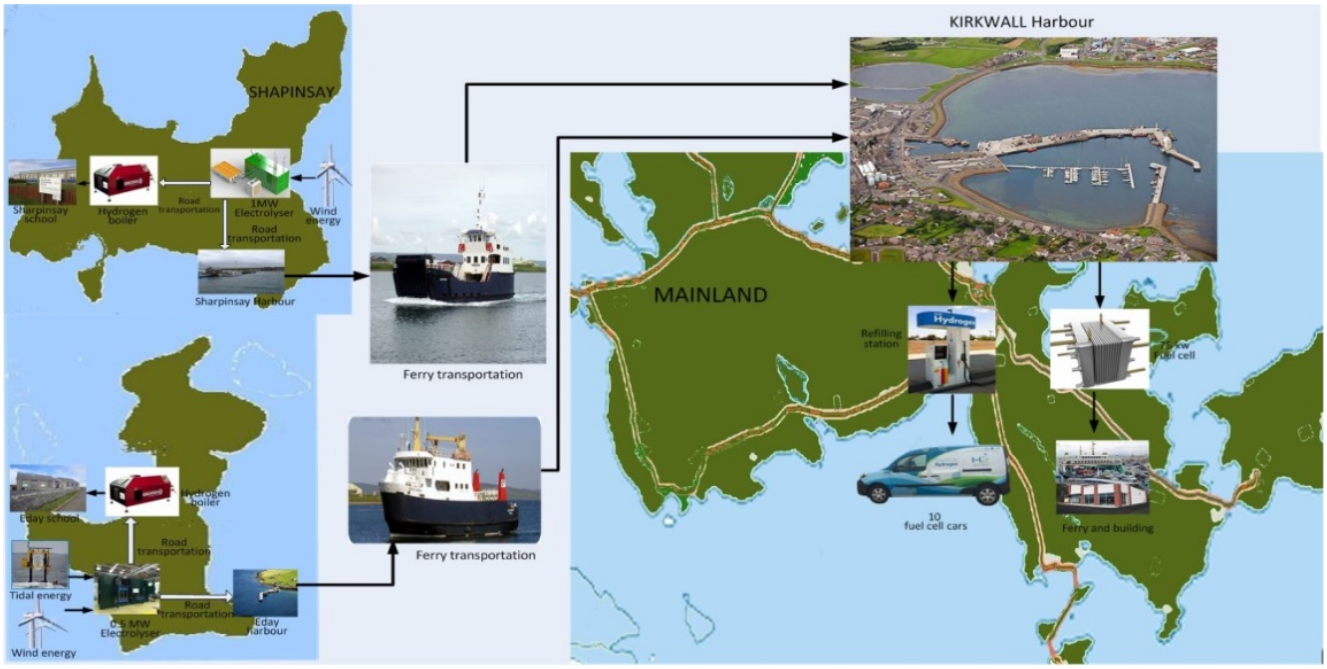

Figure 5 BIG HIT demonstration project, processes, mass and energy flows and equipment

The life cycle stage of the BIG HIT concept includes hydrogen production, hydrogen distribution, hydrogen application, and the replaced energy (Fig. 6). A “cradle to grave” approach is taken for each process of hydrogen production and application. The hydrogen production is taking place in the PEM electrolysis units. The hydrogen generation stage covers all processes in the lifecycle of PEM electrolysis from extraction of natural resources via generation of hydrogen down to the disposal of the electrolysis equipment. The electrolysis system includes electrolysis stack, cooling system, water and hydrogen separators pumps, and auxiliary equipment. The transportation of hydrogen by lorry and ferry is considered. The hydrogen application stage includes heat and power generation by a fuel cell unit, which covers the unit manufacture, operation and disposal after its end of life. It includes heat generation at the local schools by the use of catalytic hydrogen boilers. Finally, it includes hybrid vehicles that have a fuel cell running on hydrogen and a battery as the auxiliary equipment. The replaced energy is defined by the same energy services provided by traditional energy sources that would be used in the case where hydrogen would not be provide as part of the BIG HIT project.

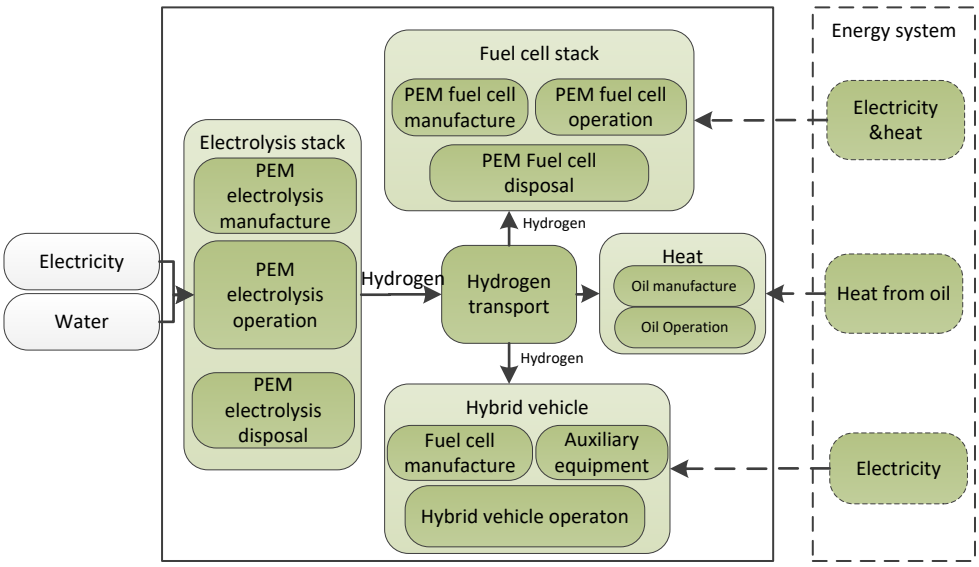

Figure 6 System boundary of BIT HIT project with system expansion

4.2.1 Hydrogen Production Stage

The PEM electrolyser, designed and built by ITM power, is capable of operating at high power densities and under rapid change in load. The electrolysis system includes electrolysis stacks, cooling system, water and hydrogen separators, pumps, and auxiliary equipment. The 1 MW BIG HIT electrolyser generates pressurised hydrogen at a maximum operational pressure of 20 bar. The electrolyser and the electrical control system are housed in two 20 ft ISO containers. The electrical control system is installed in one container. The other container is for the equipment associated with hydrogen generation and purification. The hydrogen generation container is split into two compartments – one containing the stacks (stack compartment) and one containing the additional equipment associated with gas purification. The electrolysis stack includes cells with anode, cathode, electrolyte, and catalyst. The electrolyte is a proton exchange membrane, which is a Nafion membrane. The catalyst is a material that facilitates the reaction of oxygen and hydrogen formation. It is usually made of platinum nanoparticles very thinly coated onto carbon paper. An electrolyser stack includes 75 cells with 415 cm2 of cell area. The estimated hydrogen production is 340 kg per day.

4.2.2 Hydrogen Transportation Stage

Both islands (Shapinsay and Eday) will implement the same methodology for transporting hydrogen to Kirkwall, the largest town on Mainland. The travel to Kirkwall, by road and by sea, implies expenses and is a time consuming process. The consortium of BIG HIT has employed a logistic company to handle the transportation.

The main equipment is five tube trailers supplied by BIG HIT partner Calvera. The five tube trailers function both as transport vessels and as hydrogen storage facilities. Calvera has designed and produced the tube trailers, which are light enough to comply with a 25 tonne weight limit of the Orkney roads. The tube trailers containing

hydrogen will be transported by road and sea from the electrolyser locations on Eday and on Shapinsay to Kirkwall pier, where the hydrogen will be delivered. The hauliers will also collect empty tube trailer from Kirkwall pier and return these to hydrogen generation plants on Eday and Shapinsay in the same return journey.

The journey on Eday from the electrolyser location and to the Eday pier is approximately 10 km and takes around 20 minutes. On the way to the Eday pier, the lorry will stop at Eday school to fill local storage to allow the catalytic hydrogen boilers to operate. After completing this journey, the lorry will then be loaded on a ferry at the Eday Pier. On arrival at Kirkwall, the lorry will go from the ferry to the fuel cell location in the harbour. The tube trailer will stay within the harbour area until it is empty. A similar journey will take place from Shapinsay and to the Kirkwall harbour. The tube trailer will periodically transfer some hydrogen into 30 kg of storage at each school to power the catalytic hydrogen boilers. The Kirkwall Harbour will contain 75 kW fuel cell unit producing electricity and heat for the harbour buildings and a hydrogen refuelling station providing hydrogen for 5 Kangoo ZE-H2 vans owned by the Orkney Islands Council.

4.2.3 Hydrogen Application Stage

The applications of hydrogen are heat, electricity, and mobility. On the islands of Eday and Shapinsay, two primary schools are heated by catalytic hydrogen boilers together with conventional oil boilers. The BIG HIT project partner Giacomini manufactures and sells high efficiency boilers, which catalytically react hydrogen with oxygen from the air (no flame). The total capacity will be 30 kW at each site.

At the Kirkwall harbour a 75 kW fuel cell unit is installed to provide heat and power to the harbour buildings (offices, waiting rooms, etc.), 'cold ironing' (provide auxiliary power) two ferries which berth at the harbour most nights. The fuel cell system is built by 3 HyRange 25 units of Proton Motor fuel cells, with a nominal power of 25 kW each.

A hydrogen refuelling station (HRS) is located on Grainshore Road, Kirkwall. This will include a tube trailer connection panel, local high pressure storage, compressor and dispenser. The 350 bar output HRS includes a compressor and 110 kg of H_2 storage. This will fuel 5 Kangoo ZE-H2 vans (Renault Kangoo electric vans fitted with a fuel cell range extender). The HyKangoo is originally a battery electric vehicle, which has been equipped with a hydrogen fuel cell range extender system. It is hence termed a Range Extended Fuel Cell Electric Vehicle (RE-FCEV). The vans will enter the vehicle pool of the OIC and be used for a variety of tasks including as day-to-day vehicles for the council's buildings and maintenance team. The vans have the feature that they can be charged from mains electricity and therefore a failure in supply of hydrogen will not result in them being unusable. The power generated by the fuel cell is used together with power supplied when needed from the battery to drive the electric motor. This battery is also used to store additional short-term energy generated by regenerative braking.

4.2.4 Replaced Equipment and Fuel

In order to compare the hydrogen consumption with the conventional energy (electricity, oil, and diesel), a few assumptions have been made regarding the replaced energy and fuels: The catalytic hydrogen boilers installed burn hydrogen to heat the schools on both islands to replace heat from the boiler based on oil. At the harbour, the electricity supplied from the 75 kW fuel cell unit replaces the electricity from grid and heat from a boiler. The Renault Kangoo ZE-H2 FC vans, modified by Symbio replace the standard Kangoo vans based on diesel.

5 Life Cycle Inventory

Life Cycle Inventory (LCI), where data collection is performed, includes calculation and allocation procedures. LCI is the accounting of everything involved in the system of interest. It consists of detailed tracking of all the flows in and out of the product system, including resources or raw materials, energy by type, water, and emissions to air, water and land by specific substance. Throughout the life cycle of hydrogen, some processes are used at several life cycle stages, such as the use of and combustion of fuels, the use of electricity from the grid, and transport by lorry and by ferry. This section describes the inventory data (i.e. the emissions associated with the production of hydrogen and related products and the application of hydrogen and related products) for these general processes, also termed background data in some LCAs.

5.1 Data Collection

The Life Cycle stages identified in the study are presented in section 4.2. The collection of high quality data is needed to produce a meaningful assessment. The up-stream processes cover fuel extraction phase and material phase; the core module covers the following lifecycle phases: the manufacture of equipment (electrolyser, fuel cell etc.) and hydrogen storage. LCI employed in each of these stages includes both primary data and secondary data. Primary data is data gathered by direct measurement, estimations or calculation from the original source. Measured data can be up-to-date and specific while calculated data is based on theoretical models and they are not affected by possible errors of individual measurements. Secondary data is data collected from literature and other published sources.

The data collection concerns three types of data, i.e. data on 1) processes within the BIG HIT partner organisations, 2) processes outside the BIG HIT consortium, 3) database and literature, which covers the data not included in the first two data types. The principle of data collection is to obtain the data from the first two sources as much as possible. When a specific desired dataset is not available, other data sources have to be used – with or without adjustments. These other data sources can be e.g. older data than desired, data from a different geographical location, or from a slightly different technology.

Since the use of electricity is the one of the most important factors, which contributes most to greenhouse gas emissions (GHG) related to the production of hydrogen, the inventory data of electricity production will be described and evaluated more in detail than the other inventory data presented in this section.

Processes related to hydrogen production by PEM electrolyser from ITM Power

The data collection for hydrogen production processes is mainly based on specific requested data provided by ITM Power. Data which is not available from ITM is estimated on the basis of other data sources as well as other LCA studies.

Company visit at ITM Power in Sheffield:

Data collection has taken place in collaboration with ITM Power. A company visit took place at the ITM electrolyser manufacture in Sheffield on the 23rd of June 2017.

Personal communication with Kris Hyde from ITM Power:

Communication with the project manager Kris Hyde from ITM Power has provided valuable information about production of electrolyser and production of hydrogen. The communication has been based on email conversations and skype meetings in the period July-September 2017.

Personal communication with Michael Diderich from CES:

Valuable information about electricity system and power capacity of Orkney has been obtained by personal communication with Michael Diderich from CES. The communication has been based on email conversations during August 2017.

Personal communication with Phillippe Suzan from Symbio FCell:

Valuable information about the Symbio Kangoo ZE-H2 for the Orkney Islands Council has been obtained from communication with Phillippe Suzan from Symbio FCell.

Processes outside BIG HIT partner organisations

Upstream processes to the hydrogen production as well as data for the reference scenario (without BIG HIT) are based on existing LCA data from the Ecoinvent database and from previous studies.

Most of the data used for PEM fuel cell stack and hydrogen boiler is secondary data taken from the Ecoinvent database. Some data adaptations have been performed, based on more recent literature reviews, experts' statements and exchanges with the manufacturers.

The inventory data for transport uses the measurement of tonne kilometre (tkm) as the reference flow. 1 tkm corresponds to the transportation of 1 tonne of goods at a distance of 1 km. The emissions related to the transportation of 1 kg of goods at a distance of 1000 km are equal to the transportation of 1 tonne of goods at a distance of 1 km.

5.2 Inventory

5.2.1 Hydrogen Production

This section presents the LCI data applied to the production of hydrogen. It was chosen to apply process-based LCI data to the production of hydrogen. The material input to be considered for the hydrogen production are: electrolyser facility, electricity, water input and other material input. The hydrogen production by water electrolysis requires very large amounts of electricity and water resource. At the hydrogen production stage, the electrolyser is installed close to the wind turbines and absorb the curtailment electricity. After the hydrogen is produced, it will be compressed and stored in a tube cylinder. In order to produce 1 kg hydrogen, approximately 58.5 kWh of electricity input is required. For the power generation and mobility applications, the low heat value of hydrogen is used, while 67% of high heat value is used for the heating applications because the high boilers efficiency is achieved by recovering energy in the exhaust water vapour from the boiler. The key parameters of electrolysis system are presented in table 1 below. The key parameters of the electrolyser system are supplied by the project partners.

Table 1 Key parameters of electrolyser system

Parameter	Unit	Value
1 MW PEM electrolyser		
Total max. hydrogen flow rate	kg/day	450
Hydrogen pressure	bar	20
Hydrogen purity	%	99.99
Conversion system efficiency	%	57
Power rating	MW	1
Maximum time at full rating	h/day	24
Water requirement		Potable main drinking water or rainwater >2bar
Operation conditions	°C	-15 to 40
Packing		Two 20’ ISO containers
Compressor 2-stage diaphragm compressor		
Type of gas		Hydrogen
Capacity	m^3/h (VN)	190
Power demand	kW	29.6
Suction pressure	bar	18
Discharge pressure	bar	205

The material input only includes the input to the electrolyser manufacture process. More than 90% of the feedstock input to the cast house is alloy metals (e.g. steel, copper, and silicon). Since the use of alloy metals can be assumed to be the same in all regions of the world, it is assumed that 100% of the feedstock to the steel is bought from the global market. Most of the data sources only provide information on the global market of steel. After use, the remaining part of the used steel can be sent to recycling locally in the plants or shipped to recycling elsewhere. This project do not include recycling process of electrolysis, but there is another EU project

called Hytechcycling (from the FCH-JU) in which recycling of HFC technologies is being examined. When the used steel is sent to recycling, this is included in the analysis as the avoided production of the corresponding 'virgin' materials. Therefore, the net weight has to be transformed into gross weights.

The materials for anode and cathode production are mainly titanium; and the catalyst materials are iridium and platinum. The anode and cathode used in the electrolysis process with PEM technology is made of titanium and carbon powder. More chemicals are consumed during manufacturing process. The process involves mixing, vibrating and pressing followed by baking under high temperature. The specific amounts of catalyst elements for the anode and cathode are confidential information for the electrolyser manufacturer and, hence, it cannot be disclosed here. Only estimated amounts have been used as input data for the analysis.

The estimated total amount of material used for 1 MW electrolysis is provide by the partner ITM Power. Recycling of these metals has not been considered. The frame and reinforcement material is stainless steel. Any other materials and chemicals in the system were also assumed to be non-recyclable or too trivial to warrant separation, and were incinerated or sent to landfill. The main material input for producing PEM electrolyser system is presented in table 2.

Table 2 Material inputs for the manufacture of 1 MW electrolyser

Material input	Component	Unit	Value
Mild steel	Container, pump, buffer tank, etc	kg	13700
Stainless steel	Air blast chiller,	kg	1100
Copper	Transformer, rectifier, cables, PLC, etc.	kg	5900
Aluminium	Transformer, rectifier	kg	1000
Titanium	Electrodes	kg	500
Catalyst materials	Catalyst	kg	0.3
Tetrafluoroethylene	Cell stack	kg	75
Polyethylene	Vessel, piping, tank	kg	300
Ion exchange resins	Resin filter	kg	100
Display panel	Siemens TP 1500 Comfort		1
Refrigerant Chiller	Lauda UC-0500 SP	kg	475
Fluids	EcoSafe FR-46, Amercian Chemical Technologies, USA	L	15

5.2.2 Hydrogen Consumption

The energy applications of hydrogen are heat, electricity, and mobility purposes. The application equipment are 75 kW PEM fuel cell unit, 30 kW Giacomini catalytic boiler, and Kangoo ZE-H2. The key parameters of main application equipment are present in table 3 below.

Table 3 Key parameters of equipment installed in the project

Fuel cell unit		
Nominal power	kW	75
Max electric system efficiency	%	50
Hydrogen consumption	kg/h	4.5
Stack size		
Length	m	0.8
Width	m	1.4
Height	m	1.8
Hybrid Electric Vehicle		
Fuel source		Hydrogen / electricity
Fuel consumption	kg/100 km	0.6
Estimated total distance	km	210000
Catalytic hydrogen boiler		
Fuel source		Hydrogen
Capacity	kW	30
Energy efficiency	%	90

The material input of producing 75 kW fuel cell unit and 30 kW boiler are present in table 4 and table 5. The data for the fuel cell is based on the Ecoinvent database. Giacomini has supplied the material input of catalytic hydrogen boilers. The material input for Kangoo ZE-H2 vans is modified from the standard Kangoo electric van. Table 6 presents the material input for fuel cell stack and auxiliaries to change the standard van into a Kangoo ZE-H2 van. The data sources are SymbioFC and Ecoivent. In table 7, the substituted energy by 1 kg hydrogen is presented.

Table 4 Material input for manufacture 75 kW fuel cell unit

Material inputs	Unit	Value
Cast iron	kg	48
Carbon power	kg	15
Polystyrene	kg	177
Platinum	kg	0.036
Steel, low-alloyed, hot rolled	kg	1200
Aluminium	kg	276
Titanium	kg	4.2
Chromium steel	kg	276
Steel	kg	1200

Table 5 Material input for manufacture catalytic boilers

Materials/fuels	Unit	Value
Stainless Steel	kg	15
Paint	kg	3.9
Mild steel	kg	200
Copper	kg	10
Aluminium	kg	24

Table 6 Material input for manufacture fuel cell stack and auxiliaries for Kangoo ZE-H2 Van

Materials/	Unit	Value
Steel, chromium steel 18/8	kg	181
Mild steel	kg	118
Polyacrylonitrile fibres	kg	18
Aluminium	kg	18
Cast iron	kg	4.8
Polystyren	kg	3.3
Platinum	kg	0.004
Titanium	kg	0.42

Table 7 The substituted energy by 1 kg Hydrogen

Substituted energy	Equipment	Unit	Value
Electricity	PEM fuel cell stack	kWh	3.04
Oil	Catalytic boiler	L	48
Desiel	Vehicle	L	9.67
Electricity	Kangoo ZE	kWh	22

Different components have different operating lifetimes. Table 8 shows the lifetimes assumed for all systems. The lifetimes correspond to the values obtained from BIG HIT partners. The lifetime of PEM electrolyser is assumed to be around 60000 operation hours with maintenance. The same assumption –around 60000 operation - has been made for the PEM fuel cell unit and Kangoo ZE-H2 Van. The lifetime of catalytic boiler is assumed to be 50 years.

Table 8 Lifetimes in years of different components by system

Equipment	Units	Value
Boiler	Yr.	50
Kangoo ZE-H2 Van	Yr.	10
PEM electrolyser	Hours	60000
PEM fuel cell unit	hours	60000

6 Life Cycle Impact Assessment of BIG HIT Deployed Solutions

Life Cycle Impact Assessment (LCIA), where the potential environmental effects, related to the results of the inventory and emissions, are evaluated. Emissions and consumption of resources are evaluated at every stage of the life cycle, thus the environmental impacts from the entire life cycle of products and services are addressed. In this phase, the inventory results (or emissions) per functional unit are transformed into easier interpretable impact categories (Fig 7). The number of inventory results included in an LCA is typically several hundred, while the number of included impact categories is more limited. Therefore, LCIA is normally necessary in order to be able to interpret the results. The impact of each emission or resource consumption is modelled quantitatively, according to the environmental mechanism (see Figure 7). The result is expressed as an impact score in a unit common to all contributions within the impact category by applying the so-called characterisation factors. In the LCIA phase, three steps are considered: characterisation, normalisation, and weighting. In the characterisation process, the inventories results are transformed into impact categories and the results are presented as impact indicators. In the normalisation process, the normalised results are divided by a reference (typically the total contribution to the impact category per citizen per year). In the weighting process, the magnitude of the environmental impact can better be assessed. The unit of the normalised results is person equivalents.

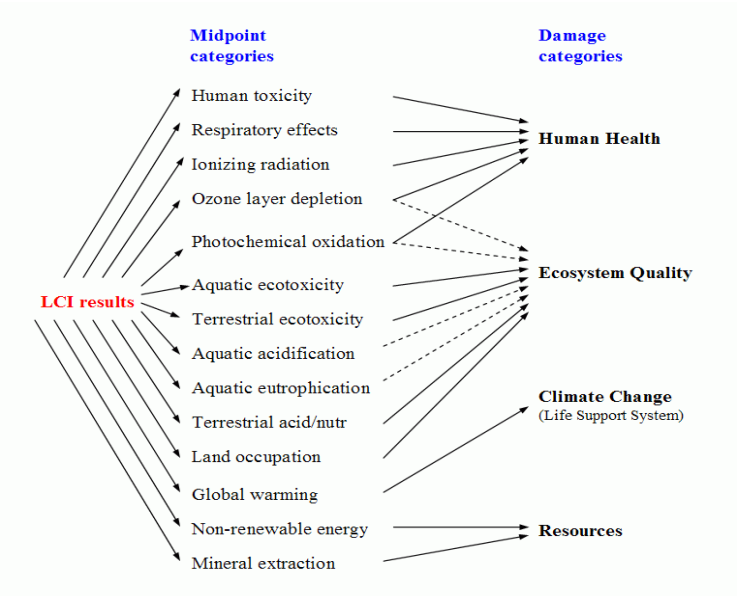

Figure 7 Impact framework, linking LCI results via the midpoint categories to damage categories of LCIA (Jolliet et al. 2003)

In this section, the LCIA results for the hydrogen application are presented. As described in the goal and scope, the focus is on the hydrogen production stage, partly because that is the stage we collect the primary data from.

The impact method is based on ILCD 2011 Midpoint where ILCD is the International Reference Life Cycle Data System (EC-JRC 2010, EC-JRC 2011). LCIA method includes 14 midpoint impact categories which are briefly explained below:

- Climate change: Global Warming Potential calculating the radiative forcing over a time horizon of 100 years. Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
- Human toxicity, cancer effects: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).
- Human toxicity, non-cancer effects: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).
- Particulate matter: Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, expressed as PM2.5 equivalents, where PM2.5 particles are air pollutants with a diameter of 2.5 micrometers or less.
- Ionizing radiation HH (human health): Quantification of the impact of ionizing radiation on the population.
- Ionizing radiation E (ecosystems): Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radionucleide emitted (PAF m^3 year/kg).
- Photochemical ozone formation: Expression of the potential contribution to photochemical ozone formation.
- Acidification: Accumulated Exceedance (AE) characterising the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
- Terrestrial eutrophication: Accumulated Exceedance (AE) characterising the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
- Freshwater eutrophication: Expression of the degree to which the emitted nutrients reaches the freshwater end compartment.
- Marine eutrophication: Expression of the degree to which the emitted nutrients reaches the marine end compartment.
- Water resource depletion: Freshwater scarcity: Scarcity-adjusted amount of water used.
- Mineral, fossil & renewable resource depletion: Scarcity of mineral resource with the scarcity calculated as 'Reserve base'.

Climate change is the impact category this study focuses on when analysing the environmental consequence of the BIG HIT solution. The other impacts are also evaluated in this report but not at the same level of detail as the GHG emissions. The software used in the analysis is SimaPro.

6.1 Impact Result

In this section, the results for seven impact categories of hydrogen energy application were calculated. This section evaluates the contribution of environmental impact categories of hydrogen application for electricity,

heat and mobility in the BIG HIT project. An overview of the characterised results of hydrogen for electricity, heat and mobility is given in table 9. The replaced energy is the scenario without a BIG HIT project in the Orkney Islands to provide hydrogen solutions. The average electricity mix from the UK grid is chosen as the replacement electricity. The replaced heat supply is taken from the fossil oil for the schools. The replaced mobility fuel is diesel based on current situation in the Orkney Islands.

The electrolysis efficiency is around 67% based on higher heating value (HHV), around 57% based on lower heating value (LHV). The efficiency of 57% is used for electricity generation and mobility applications, while the efficiency of 67% is used for heating applications. The higher boiler efficiency is achieved by recovering energy in the exhaust water vapour from the condensing boiler. Table 9 presents the impact results of hydrogen for electricity, heat and mobility. Table 9 also presents the impact results of the replaced energy and facilities. The system includes electrolysis unit, transport (both road and ferry transport), and fuel cell unit. The substituted electricity is the average electricity supply from the UK electricity grid.

The total impact of climate change for electricity production from hydrogen is estimated to be 1.62 kg CO_2 eq per kg hydrogen consumed. It can replace the climate change impact of 3.82 kg CO_2 eq the from UK average low voltage electricity. The system using hydrogen for heat includes electrolysis unit, hydrogen boiler, and transport (road transport). The substituted energy is oil, which is currently being used for heating supply. The total impact on climate change for the hydrogen for heat is estimated to be 1.61 kg CO_2 eq per kg hydrogen consumed, which can replace 9.45 kg CO_2 eq of carbon emissions from burning oil. The system of hydrogen for mobility includes electrolysis unit, hybrid vehicle manufacture (vehicle manufacture, fuel cell, battery), and transport (both road and ferry transport). The substituted energy is the diesel. Compared to the diesel vehicles, the impacts from hydrogen application of hybrid vehicle is negative regarding climate change, acidification and water resource depletion. The total impact on climate change for mobility is 4.36 kg CO_2 eq per kg hydrogen consumed, which can replace 8.39 kg CO_2 eq from carbon emissions from use of fossil fuels. The climate change impacts from hydrogen for mobility is higher than the other two applications. It is because manufacture processes of vehicles are also included in the system boundary.

The major impact from hydrogen for electricity production is the impact on climate change through GHGs, expressed in kg CO_2 eq. The total climate change impact is negative when considering the replaced energies. One of the reasons for carbon emission reduction is that the electricity used by the PEM electrolysis is generated by wind turbines. The CO_2 eq emission is mainly from the electrolysis unit, especially the manufacturing of the electrolyser unit plays a significant role, due to the materials use. If the electricity consumed by electrolyser had been generated by non-renewables, the impacts from the electricity would be much higher.

Table 10 shows the *relative* impact of the hydrogen solutions compared to that of conventional energy solutions. The results are shown for the three applications electricity generation, heat supply and mobility purpose. The numbers in table 10 have been calculated from the impact values stated in table 9. E.g. the climate change

impact by hydrogen for electricity application is only 42% of the impact from the replaced electricity (the conventional solution - electricity from the grid). Hence, hydrogen used for electricity generation reduces the climate change impact (CO_2 eq) by 58%. Likewise, hydrogen used for heat supply reduces the climate change impact by 83%, and hydrogen used for mobility purpose reduces the climate change impact by 48%.

Table 9 LCIA results of 1kg of hydrogen application for electricity, heat, and mobility purpose

	Unit	Hydrogen for electricity	Hydrogen for heat	Hydrogen for mobility	Replaced electricity	Replaced oil	Replaced diesel
Climate change	kg CO2 eq	1.62	1.61	4.36	3.82	9.45	8.39
Ozone depletion	kg CFC-11 eq	1.10E-05	9.90E-06	1.93E-05	3.15E-07	1.78E-06	7.28E-06
Human toxicity, non-cancer effects	CTUh	2.10E-06	1.92E-06	4.99E-05	8.53E-07	2.59E-07	9.79E-06
Human toxicity, cancer effects	CTUh	6.93E-07	6.31E-07	8.99E-06	1.70E-07	5.18E-08	2.08E-06
Particulate matter	kg PM2.5 eq	0.0024	0.00221	0.033	0.002	0.0111	0.014
Ionizing radiation HH	kBq U235 eq	0.10	0.092	2.19	0.41	0.66	3.0179
Ionizing radiation E (interim)	CTUe	3.47E-07	3.17E-07	7.92E-06	1.22E-06	4.42E-06	1.84E-05
Photochemical ozone formation	kg NMVOC eq	0.0069	0.0062	0.12	0.0076	0.031	0.25
Acidification	molc H+ eq	0.028	0.026	0.25	0.019	0.14	0.26
Terrestrial eutrophication	molc N eq	0.018	0.016	0.31	0.025	0.08	0.95
Freshwater eutrophication	kg P eq	0.0013	0.0012	0.033	0.0012	0.0002	0.0068
Marine eutrophication	kg N eq	0.0019	0.0017	0.032	0.0025	0.007	0.087
Water resource depletion	m3 water eq	0.0021	0.0019	0.0019	3.78	0.0023	0.0099
Mineral, fossil & ren resource depletion	kg Sb eq	0.00069	0.00063	0.013	0.0054	3.36E-05	3.47

In the hydrogen for electricity application, besides for the climate change, there is also a potential for reduced impacts with respect to human toxicity, cancer effect, ionizing radiation HH, ionizing radiation E, terrestrial eutrophication, marine eutrophication, water resource depletion and mineral, fossil & renewable resource depletion. In the hydrogen for heat application, besides climate change, there is a potential for reduced impacts with respect to particulate matter, ionizing radiation HH, ionizing radiation E, photochemical ozone formation, acidification, terrestrial eutrophication, marine eutrophication, and water resource depletion. In the hydrogen for mobility application, all the impacts except ozone depletion in this study are lower than the impacts from the conventional fuels. Even though the carbon reduction is significant by implementing hydrogen into the energy system, the other impacts like ozone depletion, human toxicity, and non-renewable resource depletion should not be ignored.

Table 10 Relative impact of the hydrogen solutions compared to the conventional energy solutions for the applications electricity, heat, and mobility

	Electricity	Heat	Mobility
Climate change	42%	17%	52%
Ozone depletion	3492%	556%	265%
Human toxicity, non-cancer effects	246%	741%	510%
Human toxicity, cancer effects	408%	1218%	432%
Particulate matter	120%	20%	236%
Ionizing radiation HH	24%	14%	73%
Ionizing radiation E (interim)	28%	7%	43%
Photochemical ozone formation	91%	20%	48%
Acidification	147%	19%	96%
Terrestrial eutrophication	72%	20%	33%
Freshwater eutrophication	108%	600%	485%
Marine eutrophication	76%	24%	37%
Water resource depletion	0.1%	83%	19%
Mineral, fossil & ren resource depletion	13%	1975%	0.4%

The relative impacts from various life cycle stages when using hydrogen for electricity production are presented in Fig. 8. Four life cycle stages are included, which are hydrogen production, fuel cell stack unit, road transportation, and ferry transportation. The largest contribution of the impacts is the hydrogen production, which accounts for more than 80% for all the impact categories. The electrolysis unit includes electrolysis manufacture and electrolysis operation (electricity and water input). During the manufacture stage, the use of metals like platinum and titanium is causing a high impact, as recycling of these metals are not considered due to limited data. The impact from the fuel cell on water resource depletion is negative, as water is generated when using hydrogen for electricity generation by the fuel cell. However, it can be questioned how real this negative impact actually is, as the water is not collected or utilised in any way.

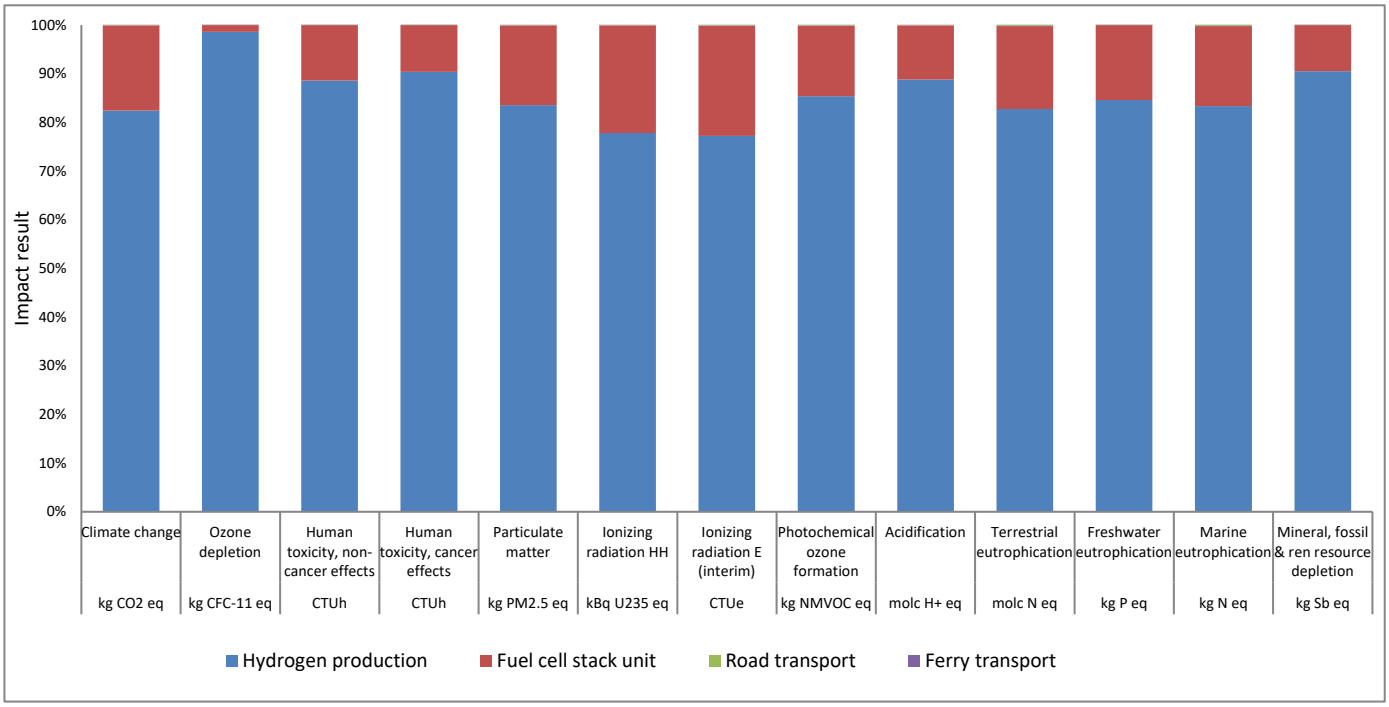

Figure 8 Relative impact of 4 life cycle stages when using hydrogen for electricity production

Fig. 9 presents the relative impacts from life cycle process of hydrogen for heat production. Three life cycle stages are included, which are hydrogen production, hydrogen boiler manufacture, and road transportation. The largest contribution of the impacts is again the hydrogen production, which accounts to more than 99% of all the impact categories.

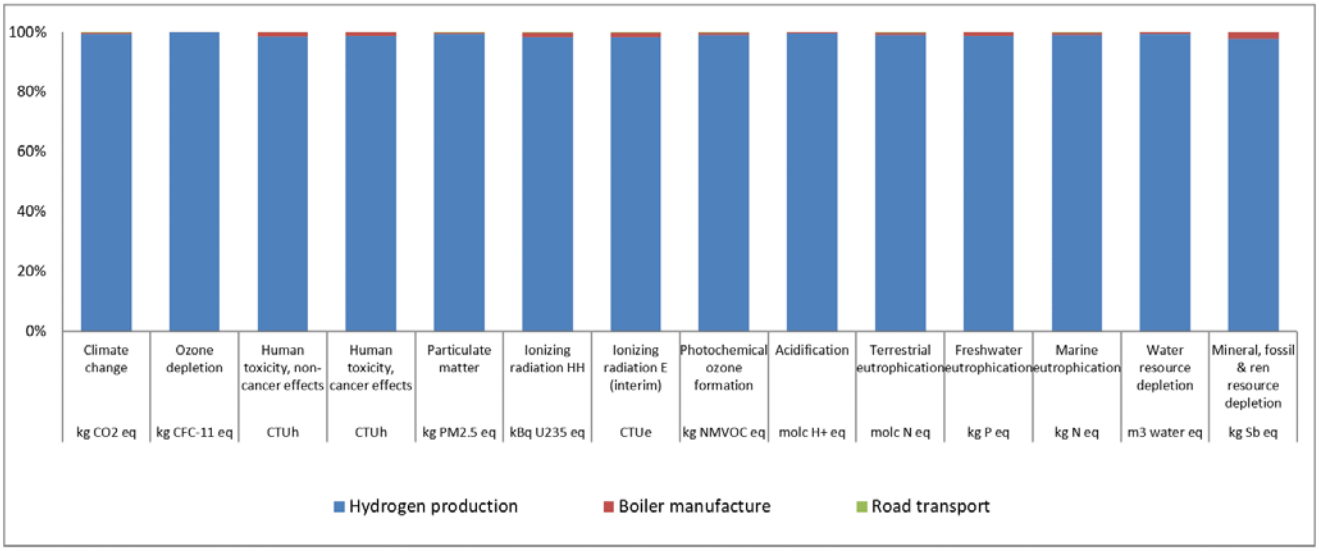

Figure 9 Relative impact of 3 life cycle stages when using hydrogen for heat supply

Fig. 10 presents the relative impact of life cycle stages when using hydrogen for mobility purpose. Unlike the hydrogen application for electricity and heat, the manufacture process of the fuel cell electric vehicle (FCEV) has the largest contribution of all the impacts except ozone depletion. The contributions from the FCEV are more than 95% of the total impacts of human toxicity, particulate matter, ionizing radiation, photochemical ozone formation, acidification, eutrophication and mineral, fossil & renewable resource depletion. The climate change contributions of hydrogen production and FCEV manufacture are 39% and 61% respectively.

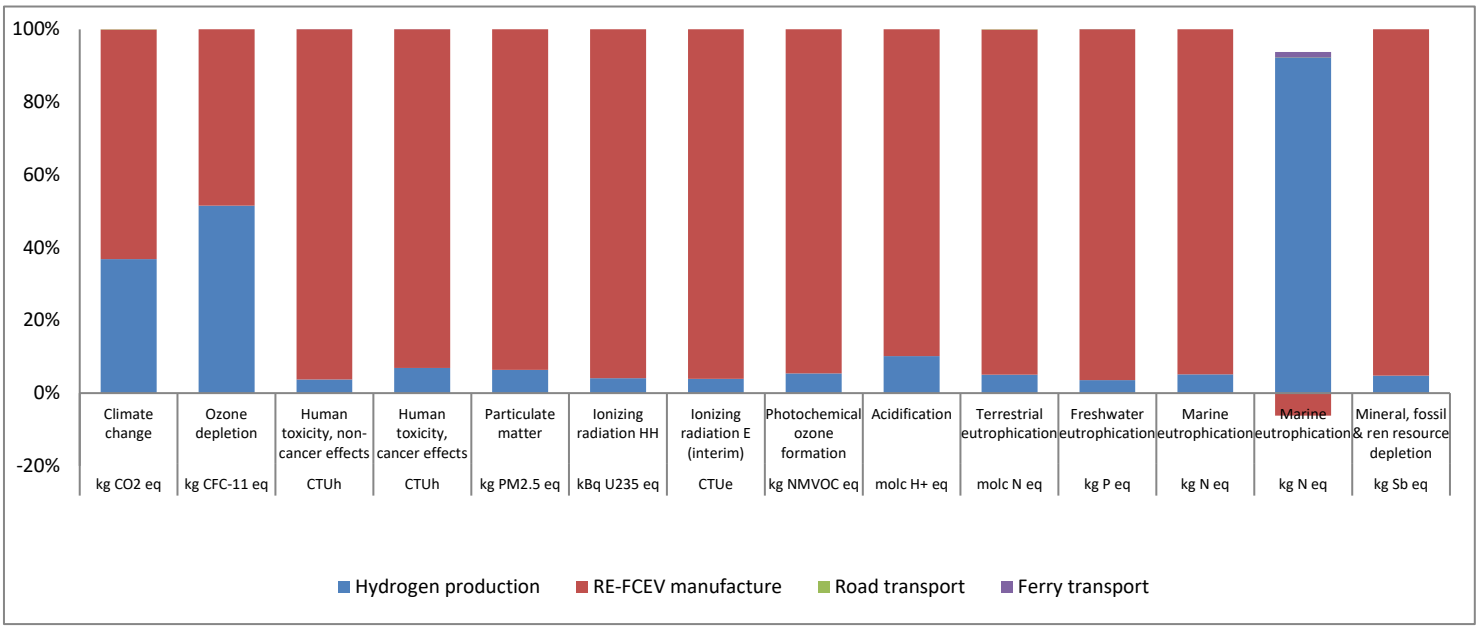

Figure 10 Relative impact of 4 life cycle stages when using hydrogen for mobility purpose on the various impact categories.

From the figures above, the impact from hydrogen production is the hotspot of hydrogen application for electricity and heat. The total impacts of producing 1 kg of hydrogen from PEM electrolysis is present in table 11. The functional unit is 1 kg of hydrogen. The system boundary includes PEM electrolysis manufacture ("facility"), electricity consumption, water consumption and maintenance. The impact of 1 kg hydrogen production by PEM electrolysis is present below (Fig. 11).

Table 11 LCIA results of producing 1 kg of hydrogen by PEM electrolyser system

Impact category	Unit	Value
Climate change	kg CO2 eq	1.61
Ozone depletion	kg CFC-11 eq	9.90E-06
Human toxicity, non-cancer effects	CTUh	1.89E-06
Human toxicity, cancer effects	CTUh	6.23E-07
Particulate matter	kg PM2.5 eq	0.0021
Ionizing radiation HH	kBq U235 eq	0.090
Ionizing radiation E (interim)	CTUe	3.11E-07
Photochemical ozone formation	kg NMVOC eq	0.0062
Acidification	molc H+ eq	0.025
Terrestrial eutrophication	molc N eq	0.016
Freshwater eutrophication	kg P eq	0.0011
Marine eutrophication	kg N eq	0.0016
Water resource depletion	m^3 water eq	0.0019
Mineral, fossil & ren resource depletion	kg Sb eq	0.0006

The PEM electrolysis manufacture ("facility") and the electricity consumption are the main contributions for 13 out of 14 impact categories. The impact of PEM electrolysis manufacture is largest for all the impact categories except for the water resource depletion. Even though the electricity is generated by a wind turbine, the electricity consumption is the second largest contributor in all environmental impact categories.

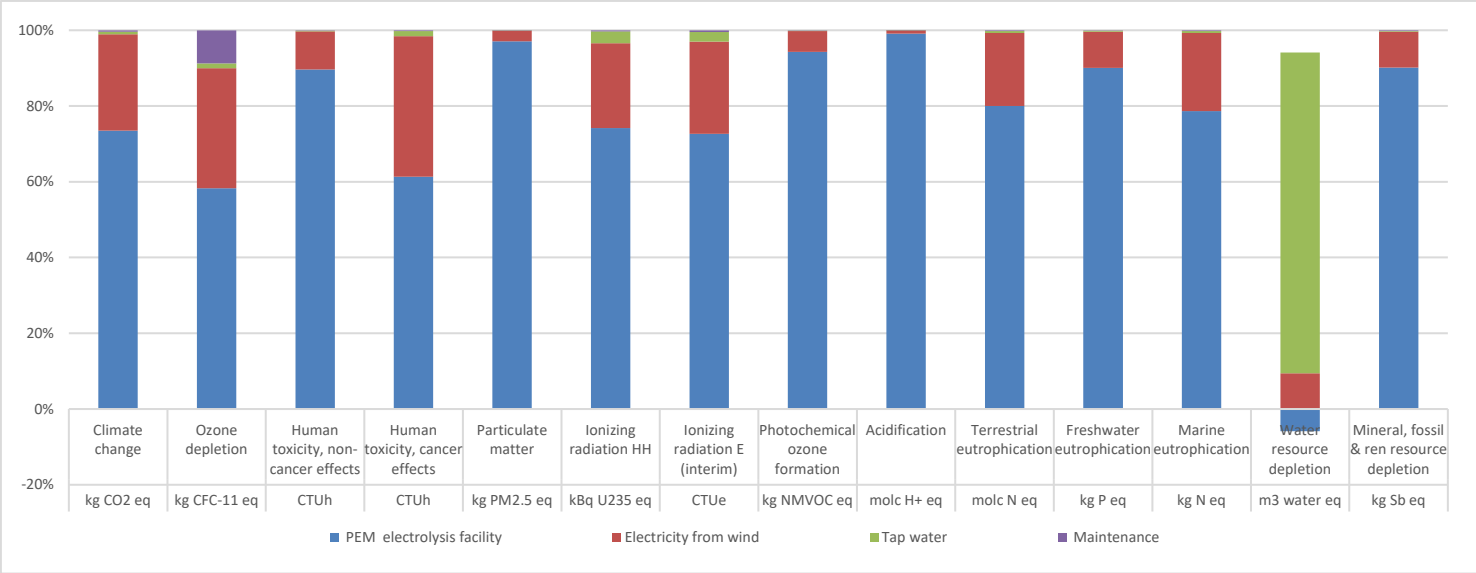

Figure 11 Relative impact of 4 life cycle stages when producing hydrogen by a PEM electrolyser.

From Fig. 11, we get the information that the PEM electrolyser manufacture is the hotspot of hydrogen production by PEM water electrolysis. Therefore, a detailed life cycle analysis of the PEM electrolyser system is conducted. The components of the electrolyser system include two 20 ft containers, electrolysis stack, absorption chiller and cooling system, water and oxygen separation, water purification equipment, auxiliary equipment, and maintenance. The results of the impacts of electrolyser unit manufacture are presented in Fig 12. The functional unit is 1 MW of electrolyser equipment.

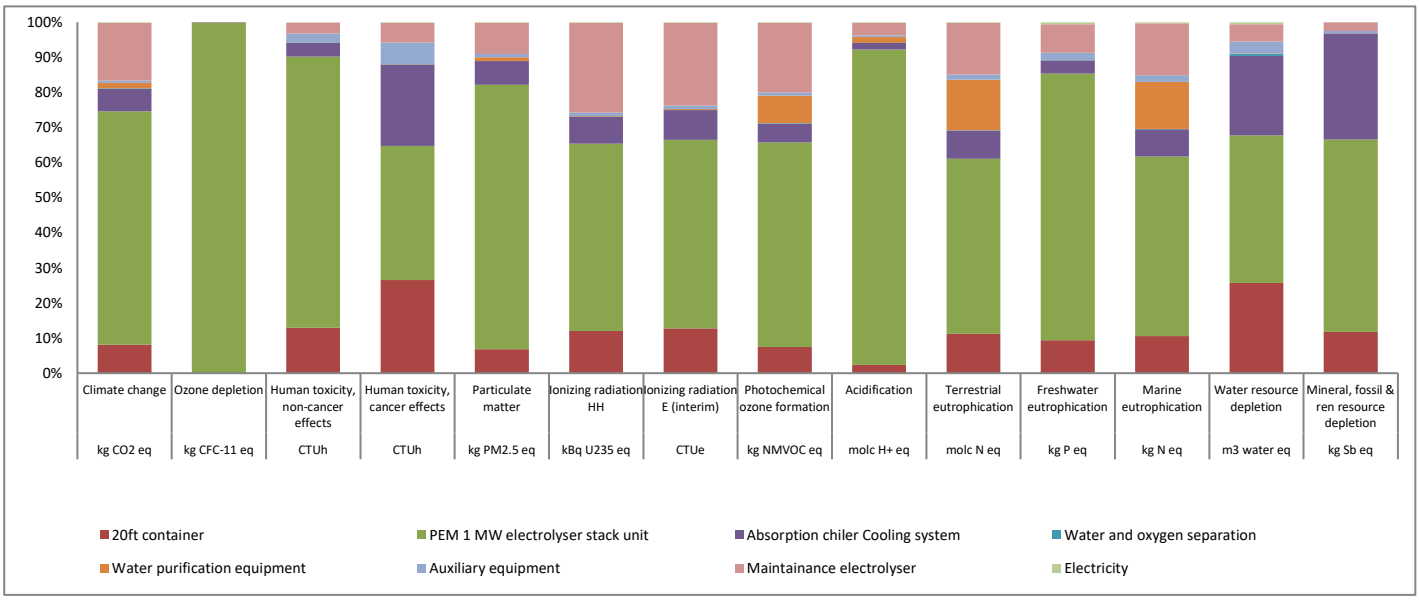

Figure 12 Relative impacts from various component when manufacturing 1 MW PEM electrolyser system

Fig. 12 shows the contribution analysis for all components of the electrolyser. The impacts from the electrolysis stack dominate. Climate change is the largest impact (see Table 11), which is dominated by the stage of electrolysis stack, followed by contributions from maintenance and container. Steel supply has the largest contribution to the manufacture of the containers. One of the reasons for the high impacts of electrolysis stack manufacture is the materials use for electrodes and catalysts. Due to lack of data, any recycling of these materials has not been included.

6.2 Climate Change

The potential carbon reduction by hydrogen for electricity, heat and mobility is present in Fig 13. The replaced electricity is the average electricity mix from the UK power grid. The replaced heat supply is the fuel oil used for the schools. The replaced transport is the diesel van. The functional unit is 1 kg of hydrogen consumed. The potential carbon reduction is 2.21 kg CO_2 eq for electricity supply, 7.83 kg CO_2 eq for heating supply, and 4.02 kg CO_2 eq for mobility purpose. For the electricity application, CO_2 emissions from hydrogen generation and application system is much lower than the conventional electricity supply. The hydrogen vehicle is compared to an internal diesel combustion vehicle with the same standard. The climate change impacts from hydrogen for mobility are higher than that from hydrogen for electricity production, due to the vehicle manufacture. However, the potential carbon reduction of hydrogen for mobility is higher than that of hydrogen for electricity. The reason is that the CO_2 emissions from mobility are much higher than that from electricity generation in general.

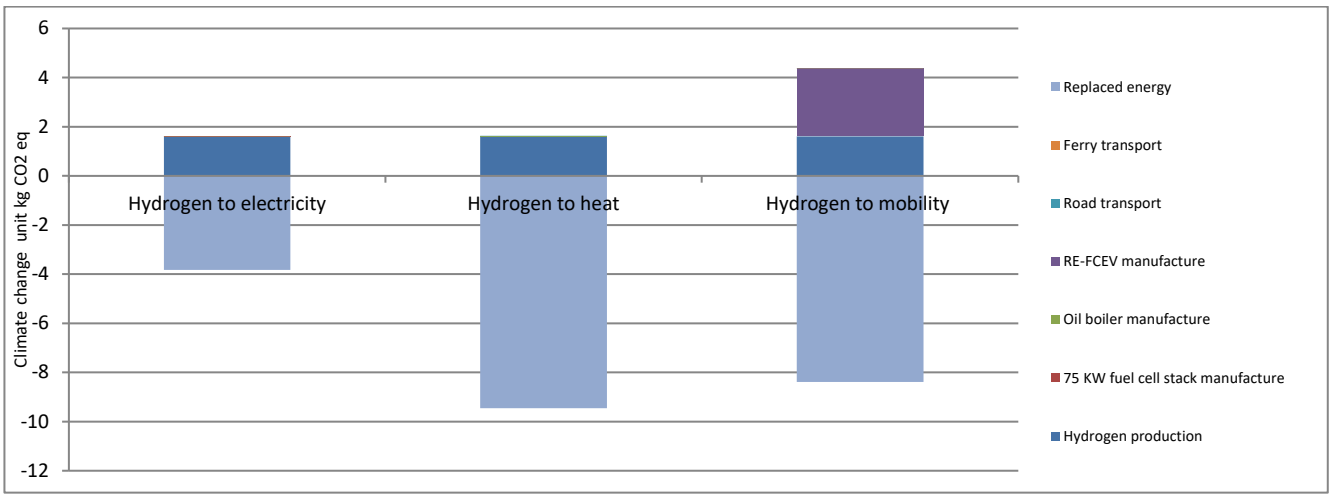

Figure 13 Potential carbon reduction of hydrogen for electricity, heat and mobility with substituted conventional energy supply

7 Life Cycle Interpretation

The final phase of an LCA project is the interpretation of the results. The purpose of this first element of interpretation is to analyse the results in this LCI/LCA report in order to identify any significant issues. Besides presenting the key results of this report, uncertainties and sensitivities are also discussed in this chapter.

For the hydrogen for electricity and heat production, the main contributor to the LCIA results is the hydrogen production. The main contributor for hydrogen application for mobility purpose is the fuel cell vehicles manufacture. Compared with the conventional energy supply, hydrogen application for mobility has the largest reduction of all the impacts. The system boundary of this LCA report is built based on the energy supply and demand in the Orkney Islands. The analysis does not consider the future change in the electricity and heat supply, which would be influenced by the UK and Scottish energy markets. The replaced transport fuel is diesel, which might be different in the future. It is difficult to predict what will happen to the electrolysis and fuel cell system at the end of their lifetime, as only few of the deployed systems have reached this stage so far. There might be a good chance that nearly all stacks will be returned to the manufacturer for internal recycling. It was not considering the recycling or dismantling of equipment of electrolyser and fuel cell system. The majority of the material used in PEM electrolysis cell and in fuel cell stack (90%) is mild steel and stainless steel. In the manufacture process, the stainless steel is coated with various metals and chemicals in the very high temperature. In our current analysis, the recycle percentage of metals (iron, copper, aluminium etc.) are based on the average recycling rate from the market. Other metal consumptions are platinum and iridium for the catalyst. Due to the high value of the Pt and Ir, all the recovery of Pt and Ir is included in the contract based on the information obtained from the industry partner. Materials are sent directly for recovery after the lifetime of electrolysis and fuel cell. We do not have the information about the recycling technology and how much energy is consumed to recycle the Pt and Ir. Commercial sensitivity about the electrolysis technology under development has made data about the construction particularly scarce. Some existing LCAs give no mention of their life cycle inventory and focus only on the impact analysis and those consulted during data gathering had to keep some of their inventory data confidential, particularly catalyst loadings in the electrolysis cell stack and fuel processing components, for commercial reasons. As a result, it is anticipated that more electrolysis stacks and fuel cell stacks will be recycled in future. This should mean that more of the materials are recycled, resulting in a reduced impact on raw material depletion.

8 Conclusion, Limitations and Recommendations

Integrating the outcome of the other elements of the interpretation phase, and drawing on the main findings from the earlier phases of the LCA, the final element of the interpretation is to draw conclusions and identify limitations of the LCA, and to develop recommendations for the intended audience in accordance with the goal definition and the intended applications of the results.

BIG HIT will create a replicable demonstration of a hydrogen territory in the Orkney Islands (Scotland) by implementing a fully integrated model of hydrogen production, storage, transportation and utilisation for heat, power and mobility. The LCA analysis is conducted based on the concept of the demonstration project BIG HIT. The objective is to provide assessment of the potential environmental impact of BIG HIT installed in the Orkney Islands. The assessment is carried on 1 kg of hydrogen produced and consumed as the functional unit. The system boundary is developed considering system expansion. This report has compared the BIG HIT hydrogen technology based solutions the Orkney Islands with situation with no hydrogen solutions available. The report includes 14 impact categories. The impact method used is ILCD midpoint.

It is seen from the impact results that the use of green hydrogen for electricity, heat and mobility purpose has potential environmental impact reductions compare to current energy supply in the Orkney Islands. The main contributor to the impacts of hydrogen for electricity and heat is the hydrogen production stage even though the electricity is generated from wind turbines. The total impact on GHG emissions as a result of electricity production from hydrogen is estimated to be 1.62 kg CO_2 eq for every 1 kg of hydrogen consumed. It can replace 3.82 kg CO_2 eq from the UK average low voltage electricity. The system of hydrogen for heat includes electrolysis unit, hydrogen boiler, transport (road transport). The substituted energy is oil which is currently being used for heating supply. The GHG emissions due to hydrogen for heat purpose is estimated to be 1.61 kg CO_2 eq per kg hydrogen, which can replace 9.45 kg CO_2 eq of carbon emissions from burning oil. The system of hydrogen for mobility includes electrolysis units, transport (road and ferry transport), and fuel cell vehicle manufacture. The substituted energy source is diesel. The total climate change for the hydrogen for mobility is estimated to be 4.36 kg CO_2 eq, which can replace 8.39 kg CO_2 eq from fossil fuel vehicles. Among that, more than 80% of that emission is from the hydrogen production process, which is dominated by the manufacturing stage of the electrolysis stack. One of the reasons for the higher impacts of electrolysis stack is the consumption of material for electrodes and catalysts. Due to the lack of recycling information of these materials, recycling is not included.

The analysis shows that in the Orkney Islands the hydrogen production will contribute to avoidance of impacts from electricity and heat production and oil consumption. The quantitative assessment of other impact categories, according to the ILCD method, suggests that no significant trade-offs with other impact categories can be found – and it appears that climate change represents a good indicator for other impacts as well.

The hydrogen production stage is identified as the hotspot of the whole system analysed. The electrolyser unit was selected for further detailed LCA analysis. The results show that the electrolysis cell stacks contribute with the largest part of the environmental impact. Further research needs to be conducted to make it possible to address the data source challenge regarding the materials used for PEM electrolysis stack (i.e. Pt, Ir, steel etc.) and recycling of these materials. Based on the assessment of its contribution to global warming, it is concluded that implementation of the hydrogen technologies as part of the BIG HIT project represents a significant reduction of greenhouse gas emissions compared to the current energy system, despite the high transportation requirements (road and ferry) which are present in the Orkney Islands.

Overall, hydrogen used for electricity generation has the potential to reduce the climate change impact (CO_2 eq) by 58% compared to the conventional energy solution. Likewise, hydrogen used for heat supply reduces the climate change impact by 83%, and hydrogen used for mobility purpose reduces the climate change impact by 48%.

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