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Business Model and Replication Study of BIG HIT

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

Business Model and Replication Study of BIG HIT

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Contents

List of Figures

List of Tables

List of acronyms

FiT ------ Feed in Tariff

ERE ----- Eday Renewable Energy

SnT ----- Surf 'n' Turf project

ANM ---- Active Network Management

ROCs ---- Renewable Obligation Certificates

OIC ---- Orkney Islands Council

DTU ---- Technical University of Denmark

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

SMEs ---- Small and Medium Enterprises

SDT ---- Shapinsay Development Trust

SHFCA ---- Scottish Hydrogen and Fuel Cell Association

CES ---- Community Energy Scotland

EMEC ---- European Marine Energy centre

GIA ---- Giacomini

CAL ---- Calvera

SYM ---- SymbioFCell

OHT ---- Orkney Hydrogen Trading

PEM ---- Polymer Electrolyte Membrane

HRS ---- Hydrogen refuelling station

LCC ---- Life cycle cost

LCA --- Life cycle assessment

S-LCA ---- Social life cycle assessment

1. Executive Summary

Due to concerns about climate change, negative environmental impacts of some fuels, and the decline in the availability of fossil fuels, renewable energy technologies are growing rapidly and becoming mature. Such technologies can provide a major share of electricity supply demand globally. However, as their market share grows, concerns about potential impacts on the stability and operation of the electricity grid, as well as economic impacts due to grid upgrading requirements, may create barriers to their future expansion, due to renewable electricity's intermittent productions and variability. 'Green hydrogen' can be seen as one of the solutions to integrate high penetrations of renewables in the energy system, using both the electricity and gas networks. At present, the 'green hydrogen' market is small and prices are high. However, costs can be driven down by upscaling the production of equipment to mass production; supply chain optimisation, and there is also still room for technology improvement. Now is the time to prepare for the integration of significant quantities of 'green hydrogen' into the energy system and gain experience from large-scale demonstration of relevant hydrogen concepts.

The BIG HIT project is creating a replicable hydrogen territory in Orkney (An island archipelago six miles offshore from North of Mainland Scotland.) by implementing a fully integrated model of hydrogen production, storage, distribution of the hydrogen across Orkney and utilised for mobility, heat and power. The BIG HIT project will use otherwise curtailed electricity from one wind turbine on Shapinsay and one wind turbine and a tidal test sites on Eday, and use 1.5 MW of Polymer Electrolyte Membrane (PEM) electrolyser to convert it into ~50 t pa of hydrogen. This will be used to provide heat to local public buildings. The excess hydrogen will be transported by ferry in hydrogen tube trailers to the Orkney islands largest town, Kirkwall, where it will be used to fuel a 75 kW fuel cell stack (which will provide heat and power to ferries when docked); and the remaining hydrogen will be used at a refuelling station to fuel a fleet of up to 10 electric-hydrogen range extended vans.

The present business model report includes a financial analysis of the demonstration project and should provide an early warning if there is anything that would require the project to be altered (for example, to negotiate negative priced input electricity). By gathering and critically examining inputs from project partners and equipment suppliers: electrolyser (ITM power), tube trailer (Calvera), catalytic hydrogen (H2) boilers (Giacomini), compressor (Hofer), fuel cell stack (Arcola Energy), Hydrogen Fuel Cell (H2 FC) van (SymbioFCell) and other stakeholders, the business model is developed within the 1st year of the project.

The cost analysis of this project considers the life cycle of hydrogen starting from the hydrogen production, transportation, and consumption. The cost includes the fixed cost for equipment and infrastructure investment and operation cost of electricity and water consumption. The functional unit is 1 kg hydrogen produced and consumed. The data collected from the project patterns and suppliers. The current analysis is based on the estimation of hydrogen production and consumption on both Shapinsay and Eday. Another objective of this report is replicability of the concept for follower territories of BIG HIT. So the cost of a replicated BIG HIT concept in the 5th year after starting BIG HIT is modelled based on the assumed capital cost reductions. Capital costs will be driven down through mass production or supply chain optimisation, and also by the technology development.

Under the two different time frames (present expectations and replication after 5 years of BIG HIT), five different scenarios are built to analyse the cost. In the first scenario S1 (current situation with limited use of curtailed energy) and the second scenario S2 (full utilisation of curtailed energy), the electrolysers on Eday and Shapinsay are directly connected to wind turbines and tidal test site. The electricity supply for the electrolyser is only from otherwise curtailed electricity. In the third scenario S3 (full utilization of electrolysis capacity and the consumed electricity from curtailed electricity), the fourth scenario S4 (full capacity of electrolyser and electricity from both curtailed electricity and power grid), and the fifth scenario S5 (full capacity of electrolyser and the consumed electricity from power grid), the electrolysers are connected to both the wind turbines and tidal test sites and the electricity grid. In the scenarios S3, S4, and S5, it is assumed that the electrolysers can operate at full capacity and run continuously at 24 hours per day. Further it is assumed, that there is a consistent demand of 'green hydrogen' on the market. The difference between the otherwise curtailed electricity and grid electricity is the price. The otherwise curtailed electricity would generate an income from Feed in Tariff (FiT), which also lead to the motivation for the hydrogen producer by using the curtailed electricity. In the current BIG HIT situation (S1) the cost of hydrogen production is calculated to be 9.87 £/kg on Shapinsay and 5.17 £/kg on Eday. Two reasons cause the cost of hydrogen production to be lower on Eday than on Shapinsay. Firstly, hydrogen produced on Eday has the priority to be transported to the fuel cell in Kirkwall, which means there would be no hydrogen unconsumed on Eday. Secondly, the cost of electricity consumed by electrolyser on Eday is less than that on Shapinsay. The difference is made by Eday Renewable Energy ltd. (ERE) sharing their FiT with the project Surf 'n' Turf (SnT) and the BIG HIT project where Shapinsay Renewables Limited, a child company of Shapinsay Development Trust (SDT) does not have the same agreement for the BIG HIT project by now. If the curtailed electricity from the wind turbines could be fully absorbed and the produced hydrogen would be transported and consumed consistently, the cost of producing hydrogen will decrease to 6.92 £/kg on Shapinsay if the agreement of electricity cost is same with that in S1. If the electricity cost is based on FiT, the cost of producing hydrogen will decrease to 2.52 £/kg presented in S2. With increasing of the running capacity, the cost of producing hydrogen can decrease to -2.33 £/kg with FiT support. In the replicated BIT HIT scenarios, the costs of producing hydrogen on Shapinsay are 9.02 £/kg and 2.00 £/kg in S1 and S2, respectively. If there would be no FiT for renewable electricity production in the future, the cost of hydrogen production will be 12.38 £/kg and 13.21 £/kg on Shapinsay and Eday, respectively (S5). The major cost comes from the cost of the electricity consumed from power grid. In the replicated BIT HIT project scenarios, the cost can decrease to 12.34 £/kg and 13.12 £/kg on Shapinsay and on Eday. This difference between from Shapinsay and Eday is due to the different capacity of electrolyser, 1 MW and 0.5 MW respectively.

The utilizations of hydrogen considered in this demonstration project are heat, electricity, and mobility. The replaced conventional energy sources are oil for heat, electricity from power grid, and diesel for mobility. The functional unit is defined as 1 kg hydrogen consumed. The costs of conventional fuels are obtained from the market price. The amounts of conventional fuels are calculated based on the same amounts of energy obtained from 1 kg hydrogen. The considered system boundary includes the hydrogen production process, hydrogen transportation, and hydrogen consumption. At each stage, the data has been collected from the project partners and equipment suppliers/manufacturers. The cost of hydrogen is calculated through the life cycle of hydrogen production and consumption. The suggested price of hydrogen in order to offer a cost-competitive solution is estimated. If the purpose is to supply heat (by boiler), the competitive hydrogen price is estimated to be between 1.22 £/kg and 1.28 £/kg without or with considering CO_2 emission cost. If the purpose is to provide electricity and heat through a fuel cell unit, the competitive hydrogen price is between 1.48 £/kg and 2.97 £/kg without or with considering CO_2 emission cost. If hydrogen is used as fuel for hydrogen fuel cell vehicles, the competitive price level of hydrogen is estimated to be 8.85 £/kg and 8.46 £/kg without or with considering CO_2 emission cost.

By the comparison of the total costs for a certain heat, power or mobility service, between hydrogen technologies and conventional technologies, it is concluded that mobility is the application where hydrogen is closest to offer a cost-attractive proposition to the conventional technology, i.e. mobility using diesel as energy source. In the present scenarios, hydrogen is not close to being cost-competitive for neither heat purposes nor power purposes.

2. Report Objective and Scope

The BIG HIT concept has been developed on the basis that this demonstration will be positioned to expand the scope of the hydrogen production and application in future, and with the objective to enable replication the technical and commercial solutions developed through the project in other areas in Europe and other continents. The BIG HIT is not only to initiate the delivery of the Orkney hydrogen strategy, but ultimately to initiate a wider market for hydrogen and fuel cell technologies.

The main objective of the replication business report is to provide a calculation tool for decision-makers regarding cost impacts for replicating the BIG HIT project to other EU isolated/remote regions in the future. Three steps are taken to achieve the objective.

1. Establish the optimum business model for the integrated hydrogen energy, transport solution in Orkney.

2. Establish a replication methodology and the applicability of these business models for to other EU hydrogen territories

3. Calculate the investment and operational cost and the generation of cash flow projection of the hydrogen territory.

The basic premise explored in this report is that large amounts of electrolytic hydrogen can create a new energy paradigm where 'green hydrogen' is integrated as an energy vector in a sustainable integrated energy system, to supply not only local transport fuel but also heat and power requirements. The BIG HIT project concept aims to maximise the use of local renewable resources by using otherwise curtailed energy that cannot be integrated into the local grid (or exported to the mainland) to produce hydrogen by water electrolysis. Another aim of the BIG HIT project is to raise awareness of hydrogen as a viable, safe, and versatile energy vector that can play a central role in social and economic challenges faced in remote communities and environmental pressure from global energy sector.

3 Introduction

The Orkney islands containing 20 inhabited island with a total population of 21500, have around 77 MW of installed energy generation with about 66 MW installed renewable electricity generation (11 MW of wave and tidal, 5 MW micro generation and 50 MW of wind)(SSEPD 2014) (Fig. 1). The local demand for electricity as a proportion of the winter peak demand, as there is normally high energy demand during winter season as the businesses and residents have no mains gas so use a mix of Electricity and fossil fuels for heat. The actual electricity generation from renewables in the Orkney Islands is only a part of the total renewable capacity, which is 66 MW. 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. The electricity demand will be less then electrify generation The electricity transmission by ANM (the Active Network Management system) within the Orkney islands is around 65% of the electricity demand (Fig. 1 and Fig 2). Remote communities operating a wind turbine have several challenges relating to energy, as the electricity grid is overloaded, leading to high levels of curtailment. The project is based in the Orkney Islands, which although they are technically grid connected to the Scottish mainland, the connection 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 supply and demand. In Orkney, this weak electricity grid leads to reduced security of supply, high energy bills for the end users and difficulties in balancing supply and demand, leading to recurrent curtailment of renewable sources. This otherwise curtailed generation is a zero carbon electricity leading to a low-cost source of energy that can be used to produce 'green hydrogen'. 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 and replace conventional fossil-based fuels, when the electricity demands is higher than electricity generation.

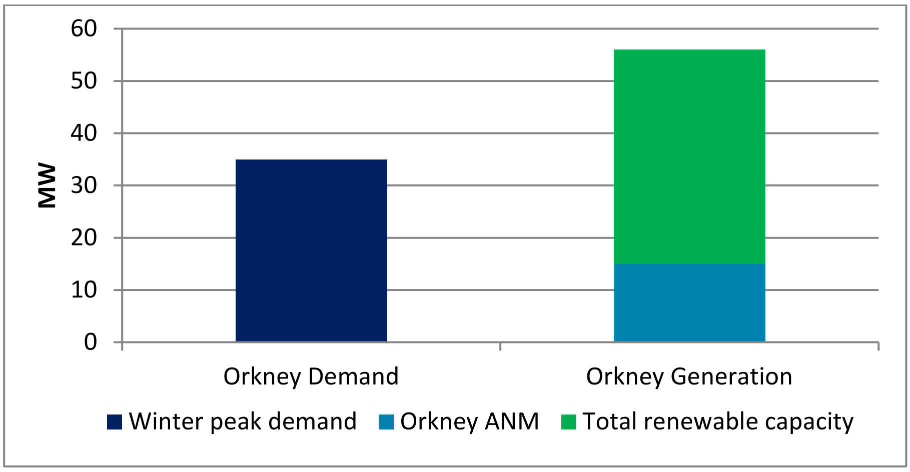

Figure 1 Renewable energy generation and demand in Orkney in 2017

Modified from (SSE 2017b)

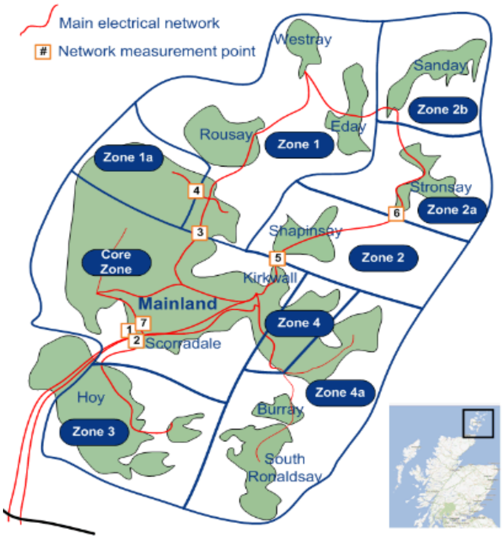

Figure 2 The main electrical grid in Orkney, showing the Active Network Management zones and main connection to the Scottish mainland.
Source: (SSE 2017a)

To demonstrate this concept the BIG HIT project will specifically use the curtailed electricity from two wind turbines and tidal turbines on the islands of Shapinsay and Eday, and use electricity to convert water into 50 t pa of hydrogen by 1.5 MW of PEM electrolyser. This will be used to heat two local public buildings (on Eday and Shapinsay), and transported to Kirkwall by 5 hydrogen tube trailers, where it will be used to fuel a 75 kW fuel cell unit, which will provide heat and power to ferries when docked, and a refuelling station for a fleet of up to 10 hydrogen-electric vans.

3.1 Project Introduction

There is one wind turbine located in Shapinsay, which is in the Orkney archipelago; there are one wind turbine and 7 tidal text sites on Eday, which is located in the northern part of Orkney. In the two islands wind and wave turbines and tidal sites together with solar energy can generate over 46 GWh/yr. of renewable electricity, and the Orkney Islands have been a net exporter of electricity since 2013. Due to the low interconnection capacity with the Scottish mainland, a large amount of electricity production is recurrently curtailed, with the associated environmental and economic penalties for the local community. Electricity used to produce the hydrogen for BIG HIT will be provided by the community-owned wind turbines on the islands of Shapinsay and Eday and EMEC tidal site on the island of Eday. At present, the wind turbines installed in Shapinsay and Eday are often switched off, losing on average more than 30% of their annual output, with their electricity output limited by grid capacity restrictions in Orkney. With the BIG HIT project, the curtailed electricity will be harvested on to produce hydrogen, which will be used to provide heating to schools, and also transported to Mainland for electricity and mobility (Fig 3).

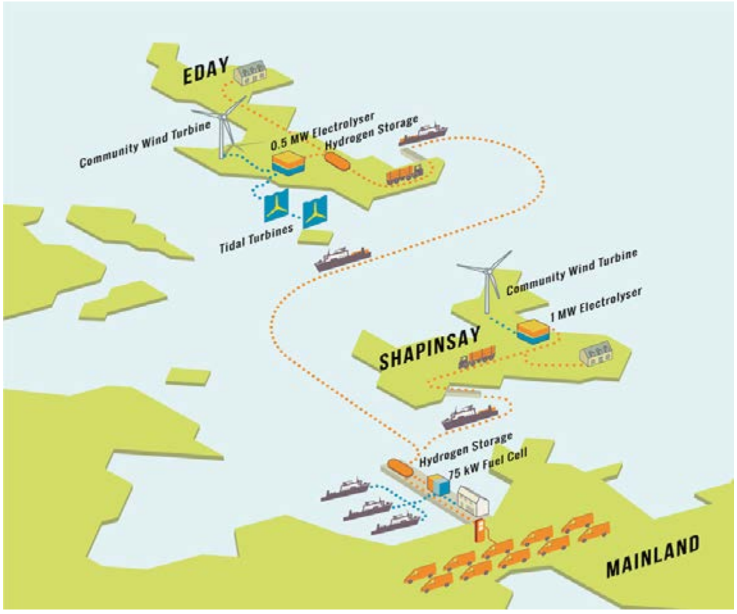

Figure 3 Schematic of BIG HIT project in the Orkney Islands

3.2 Equipment Review and Stakeholders

BIG HIT consortium includes a planning authority: OIC (Orkney Islands Council), the research community: DTU and FHA (Technical University of Denmark; The Foundation for the Development of New Hydrogen Technologies, Spain), local charities and SMEs (Small and Medium Enterprises) from the UK: SDT, SHFCA, CES, ITM, and EMEC (Shapinsay Development Trust, Scottish Hydrogen and Fuel Cell Association, Community Energy Scotland, ITM power, and European Marine Energy centre), and industrial companies and SMEs from other EU countries: GIA, CAL and SYM (Giacomini, Italy; Calvera, Spain; and SymbioFCell, France). The main equipment and hydrogen flow can be seen in Figure 4.

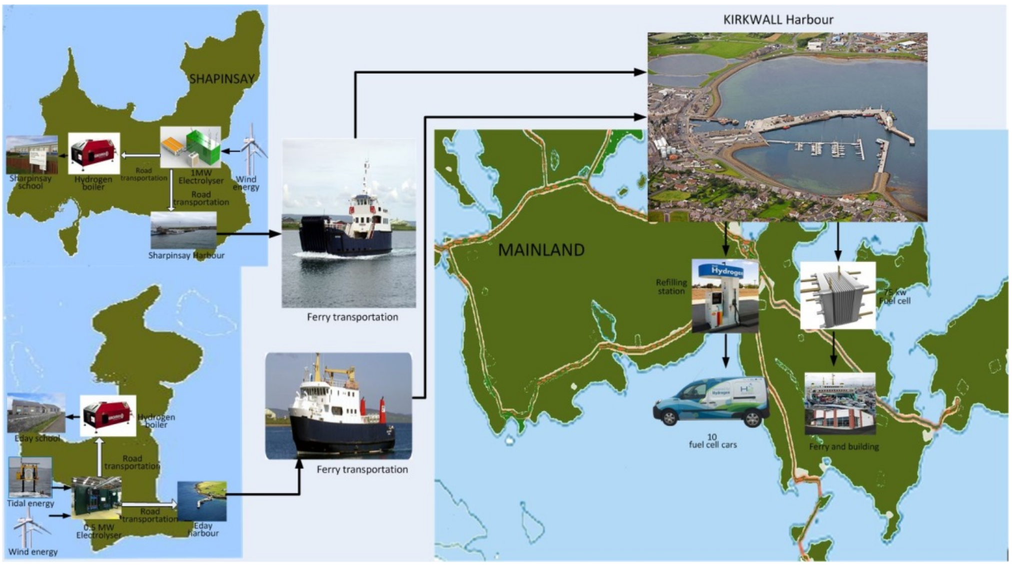

Figure 4 BIG HIT demonstration project, processes, mass and energy flows and equipment

3.2.1 Hydrogen Production

Shapinsay

When the BIG HIT project is fully implemented, the situation will be as follows: The 1 MW PEM (Polymer electrolyte membrane) electrolysis is installed on the island of Shapinsay. On the island, Shapinsay community owns 900 kW wind turbines (operated by Shapinsay Renewables Ltd, a subsidiary of SDT). ITM Power owns a 1 MW electrolysis on Shapinsay, Community Energy Scotland (CES) owns a hydrogen compressor on Shapinsay and the Giacomini catalytic Hydrogen boiler is owned by SDT. The 1 MW electrolyser will be able to capture all the curtailed electricity produced by the wind turbine on Shapinsay. The produced hydrogen will be compressed to 200 bar and then transported by tube trailers. The electrolyser is protected within a container. For more information about the features of the 1 MW electrolysers see Deliverable WP2.5 - The Design of the Modified ITM 1 MW Electrolyser.

Eday

The 0.5 MW PEM electrolyser is installed on the island of Eday. On the island of Eday, The European Marine Energy Centre (EMEC), a BIG HIT partner, owns a tidal testing site with a 4 MW connection to the power grid. EMEC's customers pay to use the test facilities, but own any power generated. It means the owners of tidal test sites will guarantee to export up to 4MW of power as long as there is no failure in the undersea cables to Scottish Mainland. Any generation by EMEC's customers above the 4MW limit would be curtailed. EMEC have the curtailed electricity connected into the BIG HIT project. Beside the tidal sites, Eday Renewable Energy (ERE) ltd. (subsidy of Eday Partnership) owns a 900 kW wind turbine with a new non-firm connection (governed by the ANM) to the grid. The curtailed electricity will be connected to the electrolysis. This 0.5 MW PEM electrolyser unit is owned by EMEC (being originally supplied by ITM) and will be used in the BIG HIT project. The produced hydrogen will be compressed and stored in 500 kg static storage equipment.

3.2.2 Hydrogen Transport & Distribution across Orkney Islands

Both islands will implement the same methodology for transporting hydrogen from the points of production on the Isles of Shapinsay and Eday to Kirkwall, Orkney's largest town. The travel to Kirkwall, by road and by sea, is an expensive and time-consuming process. And thus it is necessary to minimize the capital cost, as well as requiring particular expertise for the transportation and distribution of compressed gas hydrogen across the Islands. For this reason the consortium of BIG HIT decided to employ a logistic company to do transportation activity of hydrogen. The company of Northwards transport and distribution is responsible for the training of the drivers.

The main equipments are the five tube trailers supplied by Calvera. The five tube trailers also have the function of mobile hydrogen storage facilities. Calvera designed and manufactured the tube trailers, which are light enough to comply with a 25 tonne weight limit of Orkney roads. The tube trailers containing compressed hydrogen will be transported by road and sea from the EMEC site on Eday and SDT site on Shapinsay respectively, to Kirkwall pier, where the hydrogen will be delivered. The hauliers will also collect empty tube trailers from Kirkwall pier and return these to hydrogen generation plants on Eday and Shapinsay in the same return journey.

Currently, at the beginning of the BIG HIT project, in order to decrease the cost of distribution of hydrogen between Orkney Islands, the journey will try to combine the hydrogen from SDT site to the Shapinsay pier. On the way to the Shapinsay pier, the tractor unit will stop at the Shapinsay Public Building 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 Shapinsay Pier. On arrival in 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. The same journey will be organized from the EMEC site to the Kirkwall harbour. Under normal operation, the haulier will be expected to provide return journeys: transporting a full tube trailer from Shapinsay/Eday to Kirkwall and returning an empty tube trailer from Kirkwall to Shapinsay/Eday.

3.2.3 Hydrogen Consumption

Both islands of Eday and Shapinsay have small primary schools that are presently heated with oil. The tube trailer will periodically transfer some hydrogen to the catalytic hydrogen boilers on both islands. The Kirkwall harbour will contain a secure area for up to 2 tube trailers and a 75 kW fuel cell stack. In addition a hydrogen refuelling station will be located on Grainshore Road, Kirkwall. This will also include a tube trailer gas connection panel, onsite high pressure gas storage, a compressor and a dispenser of hydrogen for the Kangoo ZE-H2 vans.

Giacomini Catalytic Boilers

Two Giacomini Catalytic Boilers will be installed in up to two public buildings, Shapinsay Community School and a building that is yet to be agreed on Eday. This is to supply heat working together with two conversional oil heat boilers. The tube trailer will periodically transfer some hydrogen into 30 kg of storage at each building to fuel the catalytic hydrogen boilers. Giacomini manufactures and sells high efficiency boilers, which catalytically react hydrogen with oxygen from the air (no flame). These boilers are rated at 5 kW thermal power of a single burner boiler, which will be linked together to meet greater heating requirements, increasing their output to 30 kW at each site. For the detail information about the features of the Giacomini catalytic hydrogen boiler, see Deliverable 2.4 - Design of a 30 kW hydrogen boiler system - A report detailing the design of the Giacomini catalytic boilers used in the project.

Fuel Cell Stack Unit

75 kW fuel cell unit (supplied by Arcola Energy) purchased by CES. This will provide heat to some of the harbour buildings and ‘cold iron’ (provide auxiliary power) to two large ferries which berth at the harbour overnight. The fuel cell system is built by 3 HyRange 25 units of Proton Motor fuel cells, with a nominal power of 25 kW each. In addition, two tube trailers will be located to store hydrogen on the Kirkwall harbour.

Hydrogen Refuelling Station

The hydrogen refuelling station (HRS) is installed in Kirkwall, Mainland. 350 bar output hydrogen refueller, including a compressor and 110 kg of H2 storage will be installed next to the sailing club at less than 1 km from the harbour. This will provide hydrogen for up to 10 Kangoo ZE-H2 vans (Renault Kangoo electric vans fitted with a FC range extender). Five of these vans are part of the OIC's operational fleet and will be used in a variety of tasks including as day-to-day vehicles for the council's buildings and maintenance team to conduct repair of the council's housing stock. In the future, the HRS will allow private owners of FC vehicles on the island to re- fuel.

Symbio Kangoo ZE-H2 Van

The Symbio Kangoo ZE-H2 van (fuel cell vehicle, FCV) use hydrogen gas as a fuel, stored in a compact, strong but lightweight high-pressure tank. These vehicles are selected by the OIC transport managers following a review of specification for a range of FC vehicles. At the heart of an FCV is a fuel cell system which includes the fuel cell stack.

The vans can also be recharged from mains electricity and therefore a failure in the supply of hydrogen will not result in them being unused. The power generated by the fuel cell stack is used together with power supplied when needed from the battery to drive the prime electric motor. This battery is also used to store additional short-term energy generated by regenerative braking.

4 The Cost of Hydrogen Production and Consumption

4.1 Methodology

The Life cycle cost (LCC) methodology is chosen to do the cost analysis in the project. LCC summarizes all costs associated within the life cycle of a product that are directly covered by one, or more, of the actors involved in the products, which includes externalities that are anticipated to be privatized in the decision-relevant future (Asiedu, Gu 1998). LCC is an economic approach that sums up ‘‘total costs of a product, process or activity discounted over its lifetime”. The LCC is not a stand-alone technique, but is seen as a complementary analysis to the environmental life cycle assessment. LCC belongs to the group of life cycle sustainability assessment tools that focus on cash flows in connection with the life cycle of products and services. Life cycle thinking is the conceptual idea behind life cycle cost (LCC) that reflects the comprehensive approach in a completed cycle systems perspective (fig. 5). The life cycle sustainability assessment tools (LCA, LCC, and S-LCA) focus on evaluating different flows in relation to various products or services from environmental, economic, and social perspective.

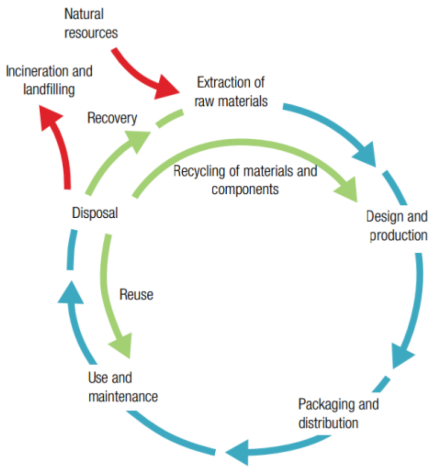

Figure 5 The concept of product life cycle thinking
Source: (UNEP 2007)

LCC takes the whole chain and spread of activities that take into consideration. It takes all the phases of the life cycle of a product or service that are required during pre-production, production, post-production, transportation and consumption into consideration. In the present analysis, the objective is to calculate the cost of hydrogen through the life cycle of hydrogen. The functional unit is defined as 1 kg hydrogen produced and consumed. The considered system boundary includes the hydrogen production process, transportation, and consumption. The cost considered three major costs of the BIG HIT projects, which are the equipment cost, operation cost, and maintenance cost. At each stage, the data has been collected from the project partners and equipment suppliers/manufactures. The cost of the equipment includes the cost of the research and development, design, construction, production and deployment. This cost can be considered as initial cost of the system. The operation & maintenance costs can vary due to the presence of future hydrogen production. The degradation of equipment might increase by higher hydrogen production in the future and therefore depreciation may be included. Operational cost includes regular operation cost of the project, such as electricity cost, water cost, salary of staff, etc.

4.2 Life Cycle Cost of Hydrogen

4.2.1 Life Cycle Cost of Hydrogen Production

Based on the theory of LCC, the cost of hydrogen production includes the equipment cost, maintenance cost, and operation cost. The service of maintenance is offered when buy the equipment. The operation cost is divided into two parts: the main material/energy (water, electricity) and operation costs (office facility, maintenance, and stuff salary etc.).

The PEM electrolysers on both Shapinsay and Eday are provided by ITM power. The compressor is supplies by Hofer, Germany. The operation cost is for the staff salary, office facility, and spare parts for the electrolyser, etc. As electricity and water are the main variable inputs related to the market, both of electricity and water consumption are taken out for further analysis (table 1).

As stated in the introduction to the document, the system to consider counts electrolyser installed along with the renewable energy systems at the islands of Shapinsay and Eday. Therefore, the current hydrogen production is considered both the renewable electricity curtailment and current hydrogen demand in the Orkney Islands. Based on the hydrogen logistic prediction from Deliverable 2.1 - Equipment Review and Modelling of the Logistics Operation, the potential hydrogen production from PEM electrolyser on Shapinsay is 16 t/yr., and the hydrogen production from 0.5 MW PEM electrolyser on Eday is 14 t/yr. The main equipment investment is PEM electrolyser and compressor on both islands. The lifetime of both electrolyser and compressor if correctly maintained is assumed to be 20 years. The electricity and water consumption are calculated from the hydrogen production. The water and electricity consumption is estimated 18L and 66.7kWh per 1 kg of hydrogen produced respectively. The water suppled for the electrolyser is the residential water. The cost is 0.6 pence per litre of water on Orkney. Many factors affect the electricity cost for electrolyser.

The Eday community own a 900 kW wind turbine with a new non-firm connection to the grid, resulting in up to 50% of the energy generated being curtailed. This marginalises the business case for the continued operation of the turbine. The turbine will be connected to the EMEC electrolyser, such that when the curtailment signal is received from the active network management (ANM) system, energy will instead be directed to the EMEC electrolyser (assuming that the electrolyser is not required for absorbing tidal generation). On Shapinsay, SDT owns a 900 kW wind turbine. The payment from UK government is 0.14 £/kWh depends on the generation technology and the time installed. The total payment includes the generation tariff and export tariff to the grid. The electricity delivered to the electrolysers cannot receive export tariff due to non-connection to the power grid. With consulting CES and ITM, the export tariff is assumed to be 0.05 £/kWh in this report. On Eday EMEC can allow their customers to the Renewable Obligation Certificates (ROCs) around 0.28 £/kWh for their curtailed electricity from tidal test sites. They have agreed that in exchange for access to this load, they will provide zero carbon electricity to the 0.5 MW electrolyser at -0.04 £/kWh cost in total. The community pay Surf ‘n’ Turf to use the electricity. On Shapinsay the SDT can receive UK government FIT of 0.09 £/kWh for their electricity generation. BIG HIT will connect a PEM electrolyser of 1 MW capacity and a hydrogen compressor to this wind turbine to absorb otherwise curtailed electricity. In exchange, SDT have agreed to provide zero carbon electricity to the electrolyser facility at zero cost now, further low price of electricity might be possible.

Table 1 The annual cost of equipment and operation on the island of Shapinsay and Eday in 2017

Location	Unit	Electrolyser investment	Compressor investment	Operation cost	Electricity price	Water price
Shapinsay	GBP/year	63450	2780	4500	0	1848
Eday	GBP/year	32225	2780	2250	-38003	1639

Interpretation: The lifetime of electrolyser, compressor is assumed to be 20 years. The total investment divided into 20 years. The price of water is 0.006 £/L.

4.2.2 Hydrogen Transportation

Hydrogen produced in the two islands of Shapinsay and Eday will be transported to Kirkwall on Orkney Mainland and stop by the two local schools on Shapinsay and Eday to fill in the catalytic hydrogen boilers. 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 on Grainshore Road, 1 km from the Kirkwall harbour, the hydrogen refuelling station will provide hydrogen for up to 10 Kangoo ZE-H2 vans owned by the Orkney Island Council. Occasionally, the tractor unit (with or without trailer) must be transported one direction (either from Eday to Kirkwall or Kirkwall to Eday) on a single day, known as a ‘single way trip’. The pricing agreement has provision for a ‘single way trip surcharge’ to account for logistical difficulty and added cost. Northwards Orkney, a transport and distribution company, in Scotland already work all drivers within the EU drivers’ hours. The advantage of hiring the local transport company is that they have other trained staff on hand if the jobs of hydrogen transportation were to fall out with the restrictions due to ferry delays etc.

The cost of equipment includes the investment of storage equipment and tube trailer. The reason for that is some of the tube trailer will be located on the island to store hydrogen in current project planning. It might change in the future. The operation cost includes the maintenance and manage of storage equipment and tuber trail, etc. The transport/distribution cost includes the road and ferry transport fee for the logistic company (driver salary, ferry ticket, etc.) (table 2). As a summary, the transport cost is an all-inclusive cost for the driver, fuel, use of vehicle and all hydrogen loading/ unloading on Eday and Kirkwall. Journeys will typically be planned to start and finish in Kirkwall, being aware that this may be dependent on ferries. Therefore it could possibly be required the driver can overnight in the vehicle in Eday, because there might be not enough time to go back to Kirkwall on the same day.

Table 2 The cost of storage and distribution of hydrogen in 2017

Location	Unit	Storage equipment (include tube trailer for storage)	Operation cost	Tube trailer for transportation	Transport fee
Shapinsay	GBP/year	10600	14305	5281	8846
Eday	GBP/year	22062	14305	5281	10935

Interpretation: The lifetime of tube trailer and other storage equipment is assumed to be 20 years. The total investment divided by 20 years. There will be one tube trailer installed on Shapinsay to storage hydrogen, one tube trailer and a 500 kg static storage installed on Eday. One tube trailer is on the road to transport hydrogen from Eday and Shapinsay to Kirkwall. So the cost of this tube trailer will be divided by Shapinsay and Eday equally.

4.2.3 Hydrogen Consumption

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. 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. On the Kirkwall harbour a 75 kW fuel cell stack unit is installed to provide heat and power to the harbour buildings (offices, waiting rooms, etc.), 'cold ironing' (provide auxiliary power), and two ferries which berth at the harbour most nights. A 350 bar output hydrogen refuelling station (HRS), including compressor and 110 kg of H2 storage, will be installed on Grainshore Road, less than 1 km from the Kirkwall harbour. Initially it was expected to have the HRS in the harbour but due to space constraints the location has been changed to the nearest area possible. This will fuel 10 Kangoo ZE-H2 vans (Renault Kangoo electric vans fitted with a FC range extender). These will enter the vehicle pool of OIC and be used for a variety of tasks including as day-to-day vehicles for the council's buildings and maintenance team to conduct repair of the council's housing stock. The hydrogen range extender system includes a type III, 74 l, 35 MPa hydrogen tank and a 6.5 kW (gross power) PEM fuel cell stack. At this pressure, up to 1.72 kg of hydrogen can be filled into the tank. For more information about the features of the Kangoo ZE-H2 vans, see Deliverable 2.3- Design modification of the Kangoo ZE-H2 vehicles.

The equipment investment includes catalytic hydrogen boilers on Shapinsay and Eday, and static fuel cell, compressor, and Symbio H2 FC van on the mainland of Orkney. The infrastructure cost includes infrastructure for fuel cell stack unit on Kirkwall harbour and the civil works for hydrogen refuelling station on Kirkwall. The operation cost of the fuel cell for the staff and maintenance (table 3). The final products of the applications are electricity, heat and transport fuels. The main energy consumption is hydrogen. The comparison between hydrogen and conventional fuels will be conducted on the following chapters.

Table 3 The annual investment cost of equipment for the consumption side.

Location	Unit	Catalytic hydrogen boilers	Kirkwall harbour	Compressor	Static fuel cell unit	Fuel cell operation cost	Hydrogen refuelling station	Symbio Kangoo ZE-H2 FC vans
Shapinsay	GBP/year	2755						
Eday	GBP/year	2755						
Kirkwall	GBP/year		1180	4340	34310	6800	45997	11952

Interpretation: The lifetimes of boiler, compressor, tube trailer, and other facilities installed are assumed to be 20 years. The lifetime of the Symbio Kangoo ZE-H2 fc van is assumed to be 10 years, and the lifetime of the fuel cell stack unit is assumed to be 5 years. The total investments are divided by theirs' life time. One tube trailer is located by the site of fuel cell stack unit, another one is by the site of refuelling station.

4.2.4 Replaced Equipment and Fuel

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 static fuel cell stack unit replaces the electricity from grid and heat from boiler. The Symbio Kangoo ZE-H2 FC vans replace the standard van based on diesel. The lifetimes of both Symbio Kangoo H2 FC vans and the standard vans are 10 years. The equipment costs of oil boiler and standard vans are presented in table 4. As the island of Orkney is an isolated island, the cost of energy sources is more expensive than that on the mainland of Scotland. So the energy costs are mainly obtained from local energy market. The cost of CO_2 emission is average cost previous study (T W Davies 2003). The costs of the replaced fuels are presented in table 5.

Table 4 The annual cost of the replaced equipment.

	Unit	Oil Boiler (2)	Standard vans used by OIC (10)
Equipment	GBP/yr	5510	12000

Interpretation: The lifetimes of two boilers is assumed to be 20 years. The life time of the standard van is assumed to be 10 years. The cost is divided by theirs' life time.

Table 5 The cost of replaced energy resources in UK

Energy	Unit	Price	CO_2 emission cost
Electricity	GBP/kWh	0.1424	0.774
Oil	GBP/L	0.4	0.048
Diesel	GBP/L	1.1805	0.041

4 .3 Scenarios

The whole ideal of the BIG HIT project is to establish a business model which is replicable to follower territories. The present cost analysis model applies to the green hydrogen production for the follower territories. This modelling will provide an early warning if there was anything that would require the project to be altered during operation of BIG HIT or for follower territories. The actual equipment investment of BIG HIT starts from the year of 2016 and 2017. The business model will be re-examined in the 5th year (2021) to compare with what has been predicted in this report. A time gap is expected between the BIG HIT and any follower territories replication of the concept.

The technology of hydrogen production by water electrolysis and consumption (PEM electrolysis, hydrogen vehicles, fuel cell, H2 boilers etc.) are still undergoing further research and development. After consulting with the equipment suppliers of BIG HIT, two time frameworks have been considered regarding the cost decreasing, due to the technology research and development.

One scenario is **Current BIG HIT**. This is the scenario describing current equipment investment and hydrogen production and consumption. The cost/price coming in/out of BIG HIT is obtained from supplier of BIG HIT in the year of 2016/2017. The data regarding the operation data is based on the design data.

The second scenario is **Replicated BIG HIT in the 5th year**. In this scenario the replication of BIG HIT in the 5th year after stating BIG HIT (2021). The cost/price of the equipment has been estimated by consulting the suppliers.

Though the industrial hydrogen market is significant, with over 50 million tonnes consumed annually mainly in the chemical and petrochemical industry, electrolytic hydrogen remains a small proportion of the global H2 market, and has only started to gain importance (and volume) in recent years due to low carbon policies and growing occurrence of curtailed renewable electricity mainly across EU. However, the costs of electrolytic hydrogen have not yet been driven down through mass production or supply chain optimisation, and room for technology improvement is still significant. The capital costs of hydrogen production could be reduced further due to the cost reduction of the electrolyser. Furthermore, the lifetime as well as system efficiency may yet be increased through R&D efforts. Electrolyser stacks and other equipment are typically considered to reach the end of their life when their efficiency has degraded by certain points from the nominal value. In current business model, this degradation is not considered. It will be examined in the 5th year.

4.3.1 Hydrogen Production

The price a consumer pays for electricity has several components: the generation sales price (covering the generation cost, plus a margin), the cost of transmitting and distributing electricity through the power grid, and any taxes or subsidies applied by governments. The formation of wholesale electricity prices is system specific and depends on the individual market design (liberalised or regulated), the power mix, the cost of fuels (domestic or international), the extent of environmental levies (e.g. CO_2 prices, NO_x or SO_x penalty) and the extent of interconnectivity with other power systems. The sales price to the power grid, a key component of end user prices, can accordingly differ widely between countries and regions.

Although sales prices are the main driver of differences in end-user prices, subsidies, taxes, and support mechanisms can also have a substantial impact. The relationship between generation sales and end-user prices is not always straightforward. Since most renewables cannot cover their total costs from prices received on the generation sales market, this has increased the end-user price, as consumers are called upon to cover the extra cost of renewables for example through a renewable energy levy (where this is passed through in the electricity tariffs).

The major material/energy inputs of hydrogen production by PEM electrolysis are electricity and water. The electricity price in the UK is determined nationally, and therefore even when Shapinsay and Eday have curtailed energy due to high wind resource, the national electricity prices will remain at the same level.

In UK the Feed in Tariff (FiT) for wind turbine is from 0.82-42.28 p/kWh depending on the capacity and the start generating date of the wind turbine. The RO scheme (Renewables Obligation scheme) for tidal turbine is 1.8 p/kWh depending on the capacity and start generating date too (Ofgem 1st February 2017). The lower capacity of wind and tidal turbine, the higher the tariff the generator can get. The earlier the renewable generation stated to generate electricity, the higher the tariff the generator can get. According to the technology development, the renewable power generation is becoming more cost competitive to the fossil fuel technology. In the near future, when the low capacity renewable technology decommission, it will probably not need the FiT for electricity consumption from renewables. The cost of hydrogen from water electrolysis is expected to vary significantly due to the electricity price range with the intervention of renewable energy. Five scenarios have been built regarding the potential electricity price and hydrogen production from BIG HIT (fig. 6).

S1: Reference scenario: This scenario describes the hydrogen production and consumption based on the current situation of the BIG HIT project. The electrolyser consumes only part of the curtailed electricity available due to the limited hydrogen consumption (on the demand side), logistic restraints, etc. In this scenario all data is either directly from the BIG HIT project partners and the suppliers of the project or from the planning (logistic analysis and design) of the project. On Shapinsay, the hydrogen production is 16 t/yr. On Eday, the hydrogen production is 14 t/yr.

S2: Electricity only from curtailment: Scenario based on the assumption that there no electricity from renewables will be wasted. **All the curtailed electricity from the wind and tidal turbines will be absorbed** by electrolysers on both islands. The production of hydrogen depends on the total amount of curtailed energy. All the produced green hydrogen will be distributed and consumed by the market. On Shapinsay, the hydrogen production is 26 t/yr. On Eday, the hydrogen production is 16 t/yr.

S3: Electricity only from curtailment and electrolyser running at full capacity: An ideal scenario assuming that the electrolyser can **run on full capacity and that there would be sufficient curtailed electricity to cover all the needed power for the electrolysis**. All the produced hydrogen will be distributed and consumed by the market. On Shapinsay, the hydrogen production is 124 t/yr. On Eday, the hydrogen production is 62 t/yr.

S4: Electricity from both curtailment and the grid and electrolyser running at full capacity: Scenario based on the assumption that the production of hydrogen are on the priority. The electrolyser consumes **electricity first from curtailment (in the amounts available today), and then consumes electricity from the grid** where the cost is controlled by the general electricity market in the UK. All the produced hydrogen (only partly based on renewables) will be distributed and consumed by the market. On Shapinsay, the hydrogen production is 124 t/yr. On Eday, the hydrogen production is 62 t/yr.

S5: Electricity only from the grid and full capacity of electrolyser: This is considered a worst case scenario, assuming that there is neither curtailed electricity available nor FIT support for the renewables. The electricity price is then the ordinary price of electricity from the grid. The electrolyser is operating at its full capacity. The produced hydrogen is not 100% 'green hydrogen' unless electricity in UK is generated only from renewables. On Shapinsay, the hydrogen production is 124 t/yr. On Eday, the hydrogen production is 62 t/yr.

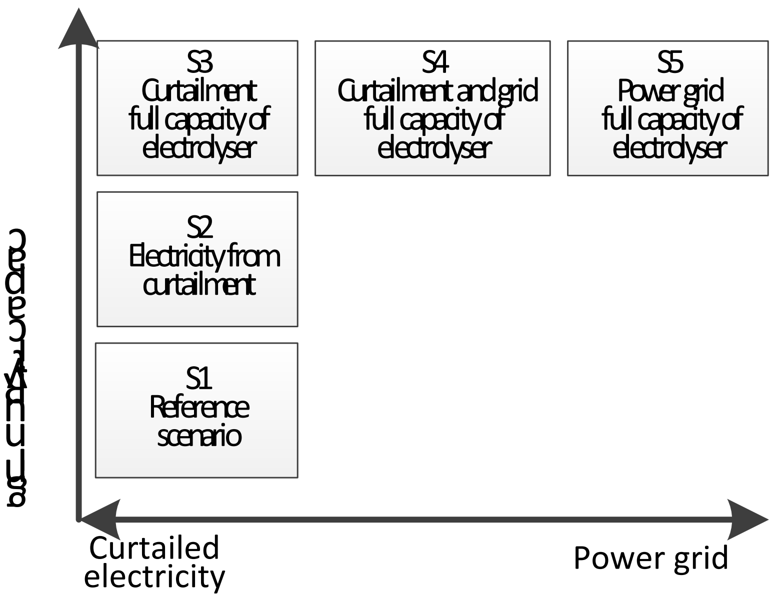

Figure 6 The formulation of scenarios
Interpretation: S1 is the current scenario based on the situation of BIG HIT in 2017, with the hydrogen demands increase and transport capacity, the curtailed electricity is assumed to be consumed by electrolyser on both Shapinsay and Eday (S2). The scenario 3, scenario 4 and scenario 5 is developed based on the full operation capacity of electrolysis, the differences between them are the electricity sources: the electricity consumption in S3 is from curtailment; Electricity of S4 is from curtailment and power grid; electricity of S5 is from power grid.

4.3.2 Hydrogen Consumption

The functional unit of consumption is calculated based on 1 kg hydrogen consumed for electricity, heat, and mobility purposes. The reason for choosing 1 kg hydrogen as the functional unit is because the potential hydrogen demand for electricity, heat, and mobility is uncertain. In order to compare the hydrogen consumption with the conventional energy (electricity, oil, and diesel), a few assumptions have been made regarding the investment and CO_2 emission cost, which are list below:

- All the equipment is assumed to keep the same function capacity regardless of the degradation each year.
- The lifetime of the equipment and infrastructures is assumed to be 20 years. The infrastructure includes the infrastructure for boiler, refuelling station, fuel cell stack. The equipment include PEM electrolyser, compressor, hydrogen storage equipment, hydrogen tube trailer, Giacomini boilers (both oil and hydrogen), and fuel cell stack.
- The total efficiency of fuel cell is assumed 80%; 40% for electricity production, and 40% for heat production.
- The annual drive distance is assumed 21278 km for both Kangoo ZE hydrogen van and Standard van. The lifetime of vehicles both fuel cell and diesel van is assumed to be 10 years.

4.4 Results of Life Cycle Cost Analysis of BIG HIT

All the cost of the BIG HIT project including electricity, water, equipment, staff salary, and transportation, etc. are collected based on the information in the UK in the year 2017. The costs of the fixed investments are collected based on the information from the partner companies or suppliers. The fixed equipment includes PEM electrolyser, Giacomini hydrogen catalytic boiler, fuel cell system, and other fixed equipment. The lifetime of most of the equipment installed in the BIG HIT project is assumed to be 20 years. Hence, the whole cost of equipment will be distributed equally by 20 years. The lifetime of Symbio Kangoo ZE-H2 FC van is assumed 10 years. The whole cost of both standard van and ZE-H2 FC van will be allocated equally to 10 years. The recycle cost/benefit is not considered in this business model because of lack of data. As electricity consumption one of the most important factors for the cost of producing hydrogen, the electricity cost is considered in the scenarios analysis. In the scenario S1, the electricity cost for electrolysers on both islands are based on the current agreements, which is -0.04 £/KWh on Eday and 0 £/KWh on Shapinsay. In the scenarios S2, S3 and S4, all of the electricity consumptions or part of the electricity consumptions come from curtailed energy. The electricity prices are assumed to be -0.066 £/kWh and 0.0559 £/kWh Shapinsay and Eday respectively, which are only consider the generation subsidies.

The cost analyses of BIG HIT current and replicated BIG HIT in the 5th year are presented in the five scenarios of electricity prices (Fig. 7). Figure 7 shows in the reference scenario (S1), the annual costs (both fixed investment and operation cost) of BIG HIT are 160 thousand GBP and 74 thousand GBP on Shapinsay and Eday respectively, which would change to 146 thousand GBP and 66 thousand GBP if the concept is identically replicated in the 5th year after starting BIG HIT. The annual cost will increase with the increasing hydrogen production. The negative cost in the S3 is because of the FiT of renewable electricity. The annual total costs dramatically increase in S4 and S5 due to the increasing of electricity price and larger hydrogen production.

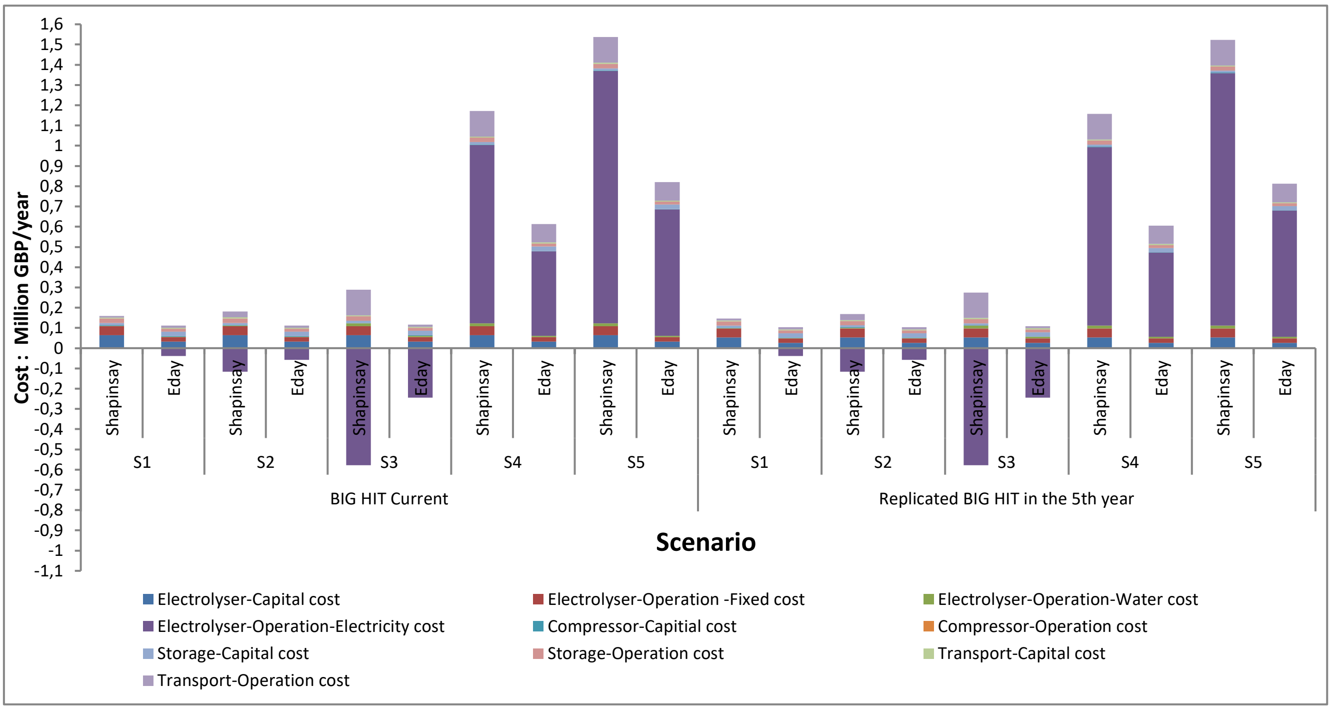

Figure 7 The annual cost of hydrogen production from different scenarios

Fig 7 presents the annual cost of hydrogen production from 5 scenarios with two different investment times. The lifetime of equipment (i.e. electrolyser, compressor, tuber trailer etc.) is assumed to be 20 years. The total capital investment is equally divided by its lifetime. The operation cost is estimated based on the hydrogen production.

4.4.1 The Cost of Hydrogen Production

The cost of hydrogen from water electrolysis is expected to vary significantly between different electricity shown in figure 8 due to a large range in electricity price. In the BIG HIT current investment, the cost of producing 1 kg hydrogen will be ranging from -2.33 £ to 12.38 £ of Shapinsay and from -2.06 £ to 13.21 £ of Eday, in the five scenarios analysed. The difference in costs between Shapinsay and Eday is due to the different FiTs of electricity generation and logistics cost, etc. In the current agreement between BIG HIT and local communities, the electricity price is much lower on Eday than that on Shapinsay. Fig. 8 also shows the cost components of hydrogen production in S1 (reference scenario) are quite different **comparing to other scenarios** especially scenario 3, S4, and S5. In the S1 the hydrogen production is constrained by the hydrogen demand from the islands of the Kirkwall. The hydrogen production in Scenario 1 is only 13% of hydrogen production in S3, S4, and S5, where the hydrogen production is the priority. The components of producing 1 kg hydrogen shift from equipment investments (mainly PEM electrolyser unit) to the operation costs (mainly electricity cost). In order to decrease the cost of hydrogen besides lowering electricity cost, increasing hydrogen demand can also decrease the share of the equipment investment cost of producing 1 kg hydrogen.

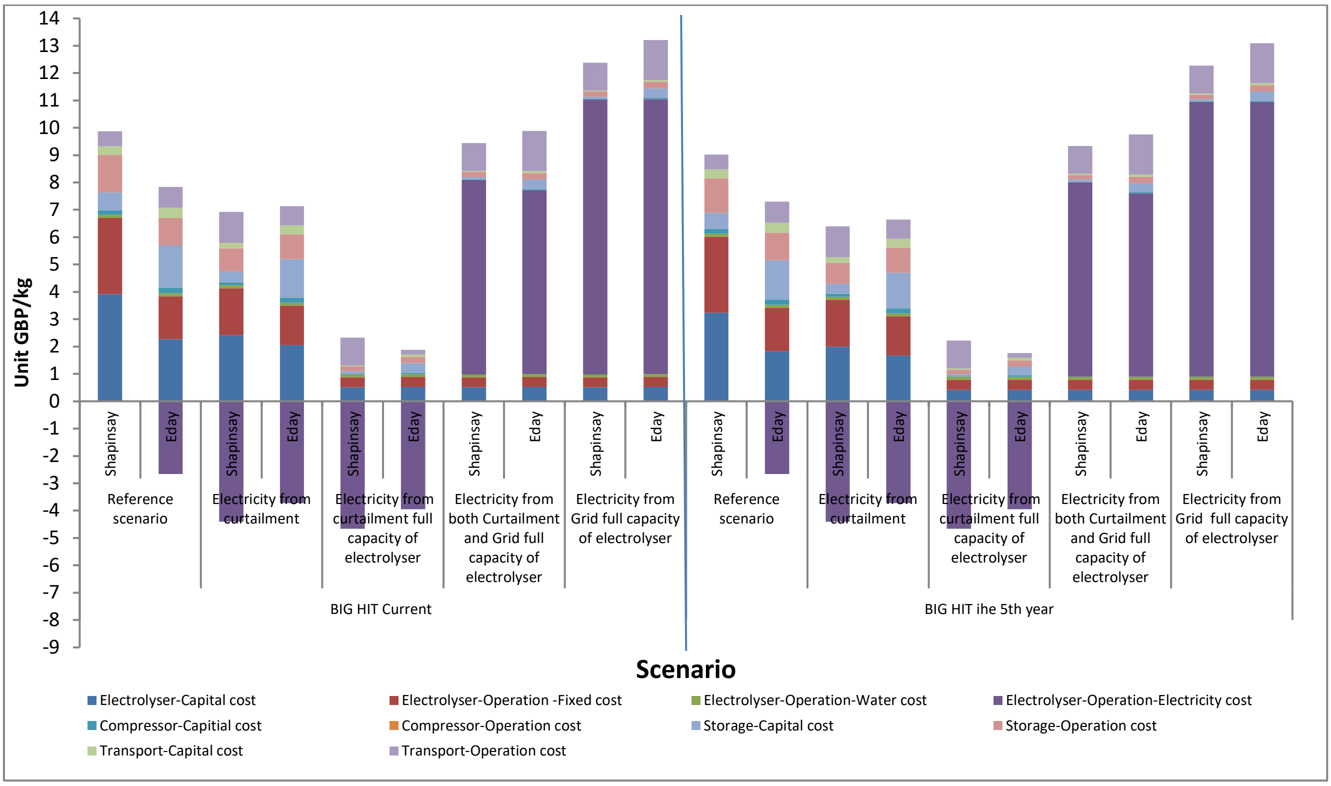

Figure 8 Life cycle cost of producing 1 kg of hydrogen in the scenarios

Fig 8 presents the cost of producing 1kg hydrogen in the 5 scenarios on the islands of Shapinsay and Eday. The total annual cost of different scenarios was present in Fig 7. The annual hydrogen productions in the scenarios on both islands are described in section 4.3.1.

Due to technology research and development, the costs of hydrogen production in the replication scenario in the 5th year after BIG HIT are lower than that in the BIG HIT current scenario with the same assumptions. The influence of the technology improvement is significant in the reference scenarios (S1), where the demand of hydrogen is constrained or limited. With increasing hydrogen demand, the influence of equipment cost becomes smaller than the electricity cost. In the long term, electricity cost plays the major role in the hydrogen production cost. The storage equipment and logistics costs are the second largest costs in the hydrogen production process. Both Shapinsay and Eday are small islands. The two islands cannot consume hydrogen by themselves after production so far. The producers have to transport hydrogen by road and ferry, which increases cost.

4.4.2 The Cost of Hydrogen Services (Consumption)

For energy purposes, hydrogen, as intermediate energy carrier, can potentially meet the demand of heat, electricity, and mobility to replace conventional fuels. The hydrogen produced from BIG HIT is called 'green hydrogen', compared to the 'brown hydrogen' which is generation from non-renewable sources. The market price of 'green hydrogen' is unknown. The price of **10 £/kg H2** is taken to do further calculation and comparison. There are two reason to choose 10 £/kg. Firstly, the price is among the calculated hydrogen production range (fig.8). Secondly, the price is chosen after consulting the industry partners. The cost of CO_2 emission is 0.018 £/kg.

4.4.3 Comparison with Conventional Technologies

The costs of hydrogen consumption for heat, electricity, and mobility are presented and compared with the conventional fuels (fig. 9). A certain service can be provided by 1 kg of H2 in terms of heat, power and mobility. The total costs of these services (including capital cost etc.) have been calculated and are shown in Figure 9, both for the hydrogen technologies and for the conventional technologies. For both hydrogen and conventional technologies, it is cheapest to obtain heat, and it is the most expensive to provide mobility when all costs are included.

By the comparison, it is concluded that mobility is the application where hydrogen is closest to offer a cost-attractive proposition to the conventional technology, i.e. mobility using diesel as energy source. In the present scenarios, hydrogen is not close to being cost-competitive for neither heat purposes nor power purposes.

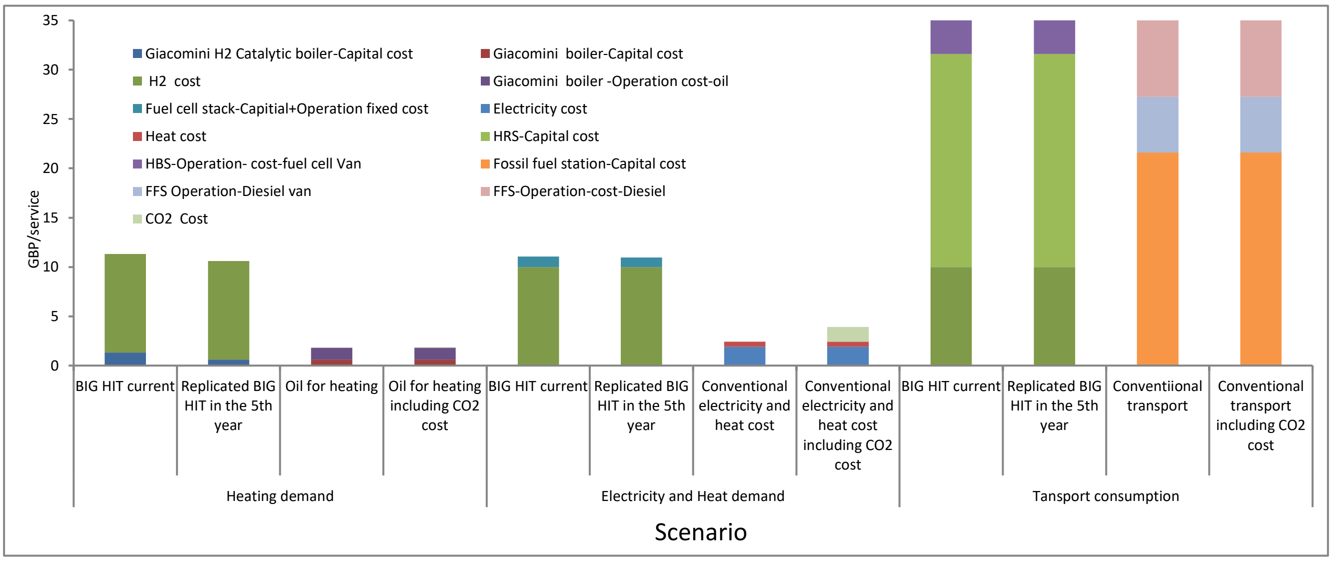

Figure 9 The total cost of services by 1 kg hydrogen consumption compare to same service by conversional fuel for heat, electricity, and mobility.

The cost of hydrogen consumed as energy source is compared with the conventional fossil energy supply in the BIG HIT project. The price of hydrogen is estimated in order to be cost-competitive. If the purpose of hydrogen is to supply heat by the catalytic boilers, then the hydrogen price is estimated around 1.22 £/kg. If hydrogen is used to provide electricity and heat by a fuel cell stack unit, the price of hydrogen should be between 1.72 £/kg and 3.21 £/kg with/without considering the external costs of CO_2 emissions. If hydrogen is used as fuel for hydrogen fuel cell vehicles, the cost-competitive price of hydrogen is estimated to be between 6.96 £/kg and 7.27 £/kg with/without considering CO_2 emission costs.

In the foreseeable future, hydrogen will probably be still more expensive than conventional fossil-based energy sources. As a consequence the integration of hydrogen into the energy market would require more support policy regulations and government intervention. Some favourable regulatory or policy frameworks could be low industrial electricity rates and high carbon prices. If hydrogen should become a widely integrated solution for example for mobility (where the technology is closest to being cost-competitive), further large-scale field trials and demonstration projects are required to provide understanding and experience, for instance to test novel electrolyser/filling station concepts. Integrated solutions with grid services and refilling stations would also be of great interest to examine further from a techno-economic perspective, as well as the injection of hydrogen into the gas network (power-to-gas concepts).

5 Business Model (BIG HIT)

The business model should determine its significance, boundaries, components, and relationships with other business aspects, such as business processes and business strategy.

5.1 Current Business Model

The current business models principally describe the ownership of hydrogen production system and the trade of hydrogen based on the BIG HIT project. Electrolytic hydrogen as an energy source is still a small market with limited customers.

The company, Orkney Hydrogen Trading (OHT) is formed in relation to the BIG HIT project. The responsibility of OHT is to make sure that the project would be generating, compressing, and transporting hydrogen by some partners, while other partners would be to pay for the hydrogen to replace fossil fuel cost. Without OHT, anyone in Orkney Island wanting to establish a green hydrogen project would need to seek a renewable source, purchase an electrolyser, transport hydrogen to the hydrogen demand site, and purchase the hydrogen demand. This is likely to require too much capital (and specialist skills) to allow projects to progress. With OHT, they will have a price quoted to them for delivery of green hydrogen to their door. This should encourage the rollout of hydrogen technologies on the islands.

ITM Power has formed the company (OHT) to trade hydrogen within the project, and use the company to encourage other hydrogen projects in Orkney. The profit will be redistributed to ITM power providing capital into the company.

As of today there are no employees and no assets of OHT Company. OHT will fulfil an administrative function and will sell hydrogen to customers, which include Orkney Island Council and the communities located in Shapinsay and Eday. The consumers will need to pay the invoices to OHT each month for the cost of hydrogen generation, cost of transportation, labour. The profit of OHT will be distributed between the OHT partners, which is only ITM power for now (Fig 10). OHT will actively seek new grant funded projects and commercial customers to expand the hydrogen trade business in Orkney. Individually, each company could not supply either the project or future customers. However, by pooling their resources they are able to supply customers in Orkney with green hydrogen at a specified price, delivered to their door.

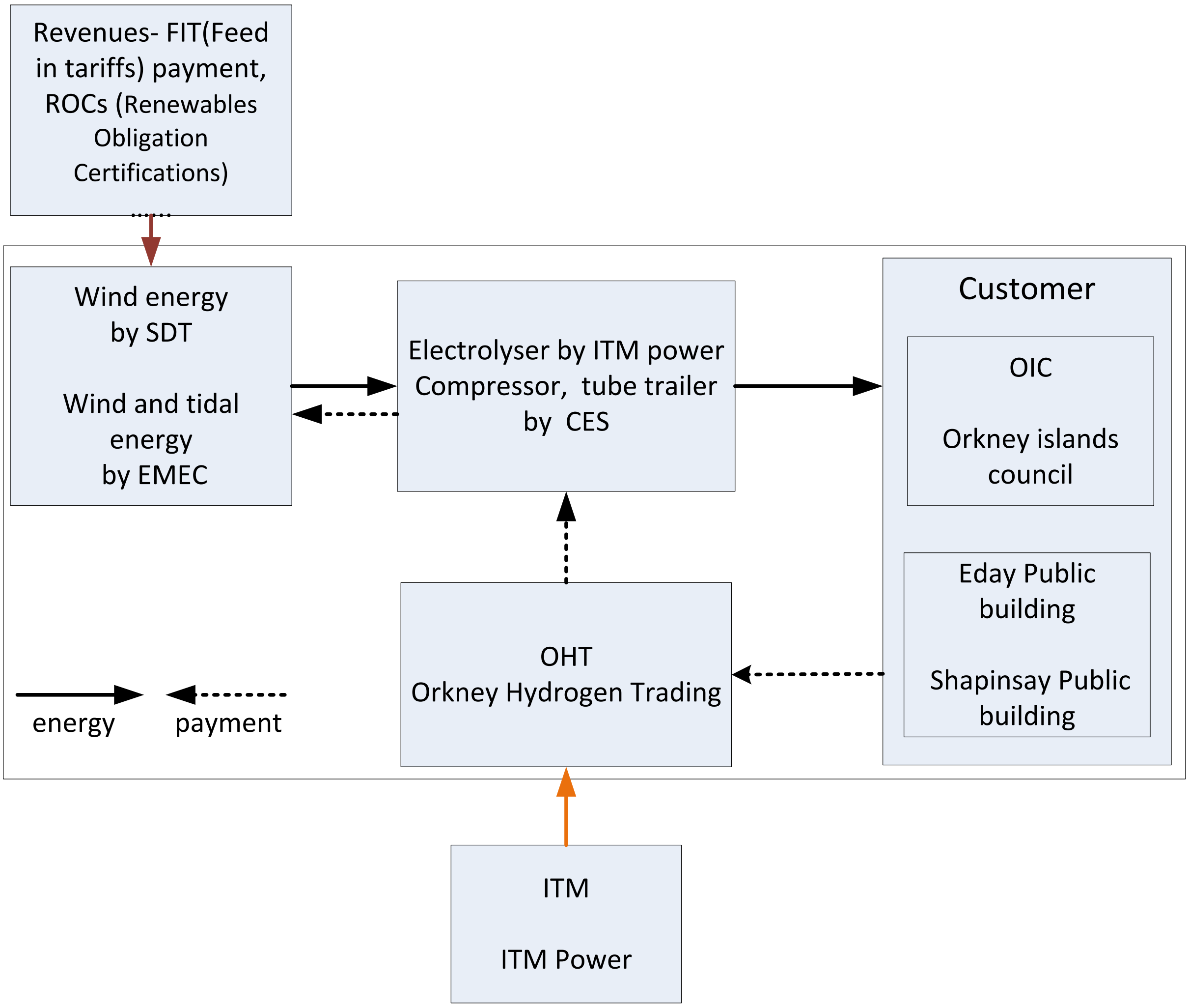

Figure 10 Current business model of hydrogen trade on Orkney

Through running OHT as a commercial business, OHT will have a greater incentive to ensure the efficient generation and transport of hydrogen, increasing the likelihood of BIG HIT being successful.

As we have analysed in section 4.4.3, the application of hydrogen and the potential customs of 'green hydrogen' play an important role in the expansion of the "green hydrogen" market. Instead the question of who controls the hydrogen trade system can became a defining factor for future business models, thus future business models are characterised in by ownership and control.

5.2 Recommendation for Business Model

Current OHT business models principally revolve around the ownership of hydrogen production systems by individuals and individual companies. As it has been discussed in section 4.4.1, the cost of hydrogen production is highly influenced by the demand of hydrogen. The business models for electrolytic hydrogen are still at an early stage, in which the industries/individual companies not only own and finance the hydrogen production system, but sometimes also managed most aspects of the distribution of hydrogen, with a small participation of traditional industrial gas companies for the time being. So at today's low level of market penetration, distributed hydrogen trade should be a central concern to increase the interest of most utilities. The future hydrogen trade should develop new, more efficient ways to deliver hydrogen, services, and financing to customers while also addressing key market barriers. The international hydrogen trade can evolve the current business model to the next level by including also "green hydrogen business models", in which the hydrogen is more attractive to a broader range of end-users. Improvements and innovations of the business model are important and are a prerequisite for the hydrogen industry to achieve a higher level of maturity and scale. The presence of 'green hydrogen' will begin to have a large impact on renewable energy operations and planning, and more generally, on how renewable utilities conduct their business.

6 Discussion

The analysis of the current cost of hydrogen begins by identifying the cash flows of life cycle hydrogen based on both fixed cost (equipment, infrastructure etc.) and variable cost (electricity, water, transport etc.). These two aspects are chosen for the following reasons. The fixed cost will likely decrease due to technology improvement and mass production of hydrogen technologies. Electricity and water are the major inputs of 'green hydrogen' production. The current costs of hydrogen production of BIG HIT are presented and compared in the different scenarios in Fig. 7, fig. 8 and fig. 9. The fixed cost plays an important role in the reference scenario both in current BIG HIT (S1) and the replicated BIG HIT scenarios (S1). It is because the hydrogen production is constrained by low demand, so the utilization ratio of the facilities is low. In order to decrease the cost of hydrogen production, it is necessary to increase the capacity utilisation of the equipment, especially the electrolyser. This requires future development of hydrogen trade to try to expand the market for 'green hydrogen', including new innovative business models.

In the cost analysis of hydrogen production in section 4.4.1, with the same amount of curtailed electricity, the costs of producing 1 kg hydrogen decreases dramatically with increasing the running capacity, which can be seen from S1, S2, and S3. It proves that based on current hydrogen production facilities, the cost can be decrease by increasing demand of 'green hydrogen'. With the same running capacity, the cost of producing 1 kg hydrogen increases from negative (S3) to the highest scenario in the calculations (S5) due to the increase of electricity cost. Driving down electrolyser system costs will contribute significantly to the commercial viability of the technology. Even though the hydrogen production cost will increase with the degradation of hydrogen production equipment, industry partners and equipment suppliers agree that there is significant potential for cost reduction of electrolyser and other hydrogen production and applications in the near future. In turn the scale-up of the electrolyser production capacity will only be achieved if the demand of 'green hydrogen' is sufficient.

The increasing demand of 'green hydrogen' will need to find more green electricity input, and the sources of electricity determine if the hydrogen will be classified as a 'green' or 'brown' energy carrier. The ability of electrolysers to produce hydrogen with an overall close to zero carbon footprint (using electricity derived from renewable energy sources) is one of the key drivers behind the interest in electrolysis. As in most EU countries, currently the electricity from the UK power grid is a mix of electricity generated from both fossil fuels and renewables. The mixed sources of electricity supply from power grid determine the mixing 'brown' hydrogen and 'green' hydrogen are unclear.

Additionally, in current BIG HIT business model, the main consumer is the local authority (OIC) on the Orkney Islands. The limited hydrogen market is the reason for the low utilisation of both electrolyser and the equipment for hydrogen applications (fuel cell and hydrogen refilling station). The size of the potential market for 'green hydrogen' is still unclear. The distinction between 'green hydrogen' and 'brown hydrogen' is also not clear on the market. In the current market, the hydrogen generated from water electrolysis based on renewables could compete directly with hydrogen produced from other sources. In foreseen future electrolytic hydrogen is not economic competitive with hydrogen from other sources due to the equipment investment and operation cost. Estimating the potential size of 'green hydrogen' markets both now and in the future is important for the renewable planning for the islands. As the development still needs further support mechanisms such as green certificates or carbon taxes for hydrogen generated from renewable electricity in order for green hydrogen to be competitive with 'brown hydrogen' and other energy sources. The increased hydrogen production would need to be transported to the Scotland, where the larger potential customs. The hydrogen has to be transported by truck first and then ferry. The road transportation is constrained by the volume and weight on the road regulations in Orkney. The maximum length and weight of the tuber trailer and truck are 12m long and 25tons of weight. The current ferry is based on the pubic ferry schedule, which is only one ferry from Eday to Kirkwall. If the hydrogen production increases in the future, the transportation capacity could become the bottleneck of the cost.

This business model is developed in the 1st year of the 5-year demonstration project. The current costs are mainly capital costs. The estimated operation costs are collected based on the interviewing with the partners and suppliers and obtained based on the design information from the project description and the logistic analysis (Deliverable 2.1 Equipment Review and Modelling of the Logistics Operation). With the running of the project in the coming years, further operation data will be included in the model to improve the certainty of the cost analysis.

7 Conclusion and Recommendations

The BIG HIT project will create a replicable demonstration of a hydrogen territory of the Orkney Islands (Scotland) by implementing a fully integrated model of hydrogen production, storage, transportation, and utilisation for heat and power. The BIG HIT will absorb curtailed energy from two wind turbines on the islands of Eday and Shapinsay and tidal test site on Eday, and use 1.5 MW of PEM electrolysers to convert the power into hydrogen. This will be used to heat two local buildings, and the rest will be transported by ferry to Kirkwall in hydrogen tube trailers, where it will be used to fuel a 75 kW fuel cell stack unit (which will provide heat and power to the harbour buildings and 2 ferries when docked). Furthermore, the hydrogen transported to Kirkwall will also be used at a refuelling station for a fleet of up to 10 fuel cell vans. The BIG HIT project has been conceived not as a stand-alone demonstration project, but as an opportunity to catalyse activities in other isolated territories where the types of solutions developed in Orkney can potentially be replicated. As such, a follower territory i.e. Malta will closely monitor the project, to learn from successes and challenges. The cost analysis will be examined again in Year 5 to compare measured values (e.g. the amount of H2 generation, cost of repairs and maintenance etc), to what was predicted in Year 1.

For the business analysis, five scenarios have been developed so far considering local factors such as electricity prices, amount of curtailed energy, government renewable tariffs, and ROCs etc. In the scenario S1 (representing the current situation of the BIG HIT project) and scenario S2 (where all curtailed electricity will be absorbed by the electrolyser), the electrolysers on Eday and Shapinsay are directly connected to wind turbines and tidal test site. In the S3 (electricity from curtailment and full running capacity of electrolyser), S4 (electricity from curtailment and power grid), and S5 (electricity from power grid), the electrolysers are connected both the wind and tidal turbines and electricity grids. In scenarios S3, S4, S5, it is assumed that current systems are designed for high utilisation of electrolyser capacity, operating at their design point, typically close to 100% load, and running continuously. There is a consistent demand of ‘green hydrogen’ on the market.

The current cost of hydrogen production is calculated to be 9.87 £/kg on Shapinsay and 5.17 £/kg on Eday in the reference scenario (S1). The production cost is mainly resulting from the equipment cost, especially the electrolyser and storage equipment. The hydrogen cost is much lower on Eday than that on Shapinsay. There are two reasons of that. Firstly, the electrolyser receives the electricity at a cheaper price on Eday (a negative electricity price) than on Shapinsay (electricity for free). Secondly, the hydrogen production from the electrolyser on Eday has priority over that on Shapinsay in the current BIG HIT, so that the hydrogen market demand is first covered by the maximum hydrogen production available from Eday, and then further hydrogen needs are covered by the production on Shapinsay. With the increasing of electrolyser’ running capacity, the cost of producing 1 kg of hydrogen will dramatically decrease, which can be seen from S1, S2, and S3. If there will be no feed-in tariffs for renewable energy in the future, the cost of the hydrogen production will be 12.38 £/kg and 13.21 £/kg on Shapinsay and Eday, respectively (S5), which is much higher than the scenarios considering curtailed energy. It proves again the importance of electricity cost to the major cost of producing hydrogen.

The cost of hydrogen consumed as an energy source is compared with conventional fossil-based energy supply in BIG HIT context. In order to be cost-competitive, the recommended retailing price of hydrogen is estimated considering different end-use applications. If the purpose of hydrogen is to supply heat by boiler, the cost-competitive hydrogen price is estimated around 1.22 £/kg. If the purpose of hydrogen is to supply electricity and heat through a fuel cell unit, the competitive hydrogen price is between 1.72 £/kg and 3.21 £/kg with/without considering CO_2 emission cost. If hydrogen is used as fuel for hydrogen fuel cell vehicles, the cost-competitive price of hydrogen is estimated between 6.96 £/kg and 7.27 £/kg with/without considering CO_2 emission cost. In our current BIG HIT scenarios (S1), the cost of producing 1 kg hydrogen is between 5.17 £/kg and 9.87 £/kg. The recommended costs of hydrogen for mobility are within this production cost range. If there is no subsidy for the electricity absorbed by electrolysers, the cost of producing 1 kg hydrogen would be between 13.21 £/kg and 12.38 £/kg, which is much higher than the recommend cost-competitive cost. Comparing with the production cost, the revenue of the hydrogen production will be negative. The 'green hydrogen' is uncompetitive in comparison to other electricity, heat, and mobility energy sources without FiT. Hence, it is found to be uneconomic to produce and consume hydrogen under current energy market conditions in Orkney/UK.

Based on the acceptable end-user market prices of hydrogen for the various applications analysed, it is found that mobility is the application where hydrogen is closest to offer a cost-attractive proposition to the conventional technology, i.e. mobility using diesel as energy source. In the present scenarios, hydrogen is not close to being cost-competitive for neither heat purposes nor power purposes. Further policy support and intervention are needed for hydrogen generated from renewable electricity in order to become competitive with conventional technology and eventually reach a mass market. The favourable regulatory or policy frameworks could be low industrial electricity prices, higher tax on fossil fuels and increased costs of CO_2 emissions. Furthermore, introduction of certificates for 'green hydrogen' may have an influence on the competition situation.

If hydrogen should become a widely integrated solution for mobility (where the technology is closest to being cost-competitive), further large-scale field trials and demonstration projects are required to provide understanding and experience with novel electrolyser/filling station concepts that incorporate innovative business models.

The business model and cost analysis of the BIG HIT concept will be available to any potential follower territories involved in the BIG HIT through the Hydrogen Territories Platform. Country specific situations like existence of subsidies or specific regulations can be included in the calculations. Other local factors affecting the electricity price should also be taken into account such as availability of curtailed energy, government renewable tariffs etc. Finally, local transportation costs, the potential size of hydrogen consumption and similar must be considered when the economic basis for a replication of the BIG HIT hydrogen concept is being evaluated.

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