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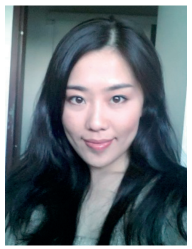

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Evaluation of smart eco-friendly public transport options in coastal cities: Towards a green future for the city of Southampton

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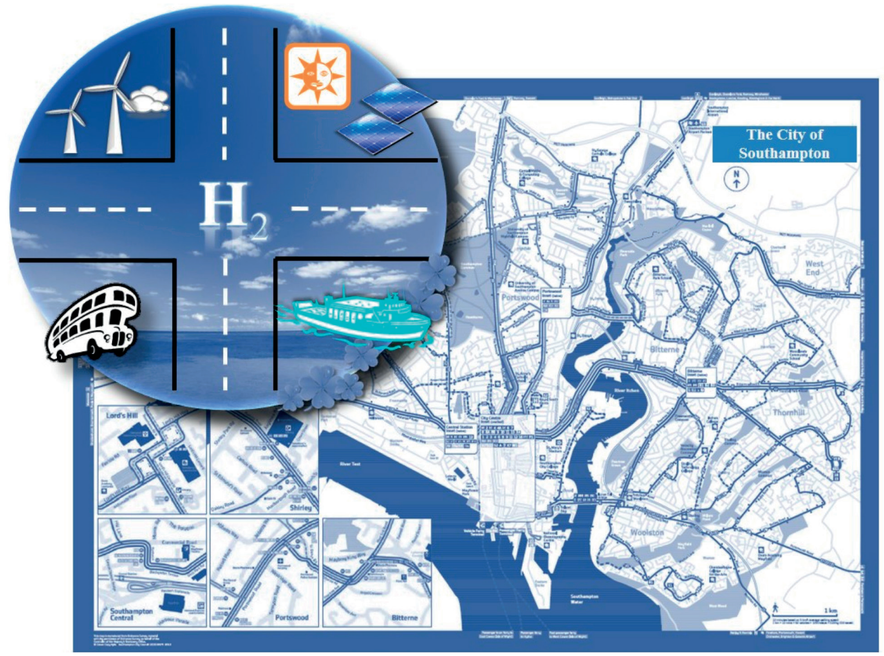

Authors: **S Chakraborty, A S Dzielendziak, T Köroğlu, K Yang**

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Foreword

The Lloyd's Register Foundation (LRF) in collaboration with the University of Southampton instituted a research collegium in Southampton between 18 July and 11 September 2013.

The aim of the research collegium has been to provide an environment where people in their formative post-graduate years can learn and work in a small, mixed discipline group drawn from a global community to develop their skills whilst completing a project on a topic that represents a grand challenge to humankind. The project brief that initiates each project set challenging user requirements to encourage each team to develop an imaginative solution, using individual knowledge and experience, together with learning derived from teaching to form a common element of the early part of the programme.

The collegium format provided adequate time for the participants to enhance their knowledge through a structured programme of taught modules which focussed on the advanced technologies, emerging technologies and novel solutions, regulatory and commercial issues, design challenges (such as environmental performance and climate change mitigation and adaptation) and engineering systems integration. Lecturers were drawn from academic research and industry communities to provide a mind-broadening opportunity for participants, whatever their original specialisation.

The subject of the 2013 research collegium has been systems underpinning coastal eco-cities.

The project brief included: (a) quantification of the environmental challenge; (b) understanding of the geo-political legal-social context; (c) one integrated engineering system for a coastal eco-city; (d) economics and logistics challenges.

This volume presents the findings of one of the five groups.

R A Shenoi, P A Wilson, S S Bennett (University of Southampton)

M C Franklin, E Kinghan (Lloyd's Register Foundation)

2 September 2013

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Special thanks go to the invited lecturers from both industrial and academic institutions, for inspiring us at the very beginning of the collegium when we were trying to define out topic. Our gratitude is extended to the following people for their sharing with us their knowledge and proving guidance as we progressed with our project: Prof AbuBakr Bahaj for sharing with us his knowledge on energy; Dr Tom Cherrett for consulting on transportation planning; Prof Ian Williams for helping us out about carbon footprint; Colin Finnegan for providing us the cost data of wind turbines; R Barry Hall from MetOffice for giving us local wind and solar data of Southampton; Mr Edward Fort from LRF and Mr Artur Lidtke for their consultations over the ferry design. In addition, we would like to thank and Ms Vanessa White as well as Mr Simon Bell from the City Council of Southampton for spending their time with us and generously sharing information which helps us in the project.

In addition, the authors would like to thank their supervisors and home institutions for supporting and encouraging them to attend this research collegium. They are Prof Steven E Lohrenz and Prof Avijit Gangopadhyay from

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Last but not least, for always brightening up the days, and providing love and encouragement, each of the authors would like to thank their individual partners, who are Miss Deniz Günal and Mr Yanyan Sha. The deepest gratitude of the authors goes to their family, for always providing unconditional and endlessly support and love. To all of you, we present this book.

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Executive Summary

Coastal regions are of economic importance to global economies but they harbor a disproportionate amount of the population. Coastal zones account for only 2% of the world's total land area but approximately 13% of the world's urban population lives in these zones. The continuous growth of population and associated climate change can adversely affect these regions in every aspect. Necessary action needs to be taken to protect coastal zones and coastal cities and make them sustainable.

Transport is one of the important sectors in a coastal city that can be seriously affected by climate change and ever increasing load from urban growth. Though development of sustainable/eco-friendly transport for cities is challenging but new innovative ideas of are emerging. Use of renewable energy source in transport is gaining popularity both in public and government sectors.

Although the current climate for renewables in transport is challenging, the analysis in this report highlights the outlook for the future. The study proposes an integrated transport system supported by a hybrid hydrogen plant from renewable energy (wind and solar) is proposed.

The findings of this study show that for a conceptual network of public transport it is economically feasible to produce and use hydrogen as an alternative to diesel. One of the important highlight of this work has been that the energy generated from solar photovoltaic could alone support the entire hydrogen demand for the conceptual transport system.

The work provides new perspective regarding implementation of sustainable transport in the city of Southampton, UK. The main contributions of this work are assessment of the availability of renewable energy (wind and solar), annual energy requirements and cost analysis.

Motivation

“You must become the change you wish to see in the world.”

- M.K. GANDHI

“Dünyada herşey için, medeniyet için, hayat için, muvaffakiyet için, en hakikî mürşit ilimdir, fendir. İlmin ve fennin haricinde mürşit aramak gaflettir, cehalettir, dalâlettir.”

(“For everything in the world, for civilization, for life, for success, the true guides are science and art. Searching for another guidance except science and art is blindness, ignorance and heresy.”)

- MUSTAFA KEMAL ATATÜRK

Outline of the study: Aims and objective

This report presents issues relating to coastal eco-city, and design and development of eco-friendly transport in a coastal city.

The first part of the study deals with understanding the broad environmental and societal problem that the coastal zones face and the need for the development of eco-friendly transports. In this part the study addresses the following general questions.

What are the threats to coastal zones and cities in general under the present and future climate scenarios and population growth?

What is the definition of a coastal eco-city and importance of eco-friendly transport?

What is eco-friendly transport and different modes of eco-friendly transport?

In the second part the study reviews and introduces renewable energy and concepts of hydrogen economy. The role of renewables and hydrogen and how they fit into transport is discussed.

For the third part, the study evaluates eco-friendly transport options in a coastal city. The aim is to design and develop an integrated transport framework that is fully supported by renewable energy sources. The potential of renewable energy sources to supply that transport framework is evaluated. The study also proposes the construction of a coastal hydrogen power plant in the city of Southampton. A cost assessment of such a plant is performed and finally the overall reduction in carbon footprint has been assessed for the city. In conclusion, the study provides some guidelines and ideas for the city of Southampton, which might help the city to achieve its goal to become a green eco-friendly city.

What are main problems and near-future goals of the city?

What are available renewable energy sources in the regions?

What are their theoretical, technical and economic potential?

What eco-friendly transport options can be implemented in the city of Southampton and how it would help the city to become a coastal-eco city?

List of Abbreviations

A yearly payment of cost

ABP Associated British Ports

ABP associated british ports

ANSI American National Standards Institute

APP application

A_{PV} Area of PV

ASME VIII Div.1 - Boiler and Pressure Vessel Code 2013 Edition

avg average

C_B operating cost (£/year)

C_{BF} fixed operation cost (£/year)

C_{BS} other variable operational cost (£/year)

C_C annual payment of capital costs of the end use conversion technology upon lifetime (£/year)

C_D recent diesel cost (£/kg)

$C_{D,H2}$ Hydrogen equivalent cost of diesel

CEA French Atomic Energy Commission

CEDI continuous electro deionizer

C_{H2} the cost of hydrogen (£/kg)

CH_4 methane

CO2 carbon dioxide

CO_2 carbondioxide

CO_2e is CO_2 equivalent

CRF capital recovering factor

C_S Service Cost (£/km)

$C_{S,Dbus}$ Service Cost of buses with Diesel

$C_{S,Dferry}$ Service Cost of ferry with Diesel

D Diameter (m) or Diesel with respect to the Section

DNV Det Norske Veritas

E energy

f Friction Factor

FC Fuel Cell

FCS Fuel cell ship

GHGs greenhour gases

GL Germanischer Lloyd

GWP global warming potential

HABs harmful algal blooms

i interest rate

IC investment cost (£)

IEC International Electrotechnical Commission

IGC International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

ISO The International Organization for Standardization

ITTC International Towwing Tank Conference

L Length (m)

LH2 liquid hydrogen

LHV Lover Heating Value

LHV Lower Heating Value (MJ/kg)

LR Lloyds Register

$\dot{m}$ Mass Flow rate (kg/s)

n life time of the component (year)

NOx mono-nitrogen oxides

P Power output

PEMFC proton exchange membrane fuel cell

P_f Packing Factor

PM particulate matter

PV Photovoltaic

PV photovoltaic

Q quantity of hydrogen (kg H_2/year)

R&D -research and development

RE renewable Energy

Re Reynolds Number

RES Renewable Energy Sources

S service demand (driven km/year)

sfc specific fuel consumption (kg H_2/km)

SOx	sulphur oxides
T	Time Period
tCO_2	tonnes of carbondioxide
TINA	Technology Innovation Needs Assessment
U1	Unilink Bus Service
U1	Unilink bus service
V	Velocity (m/s)
WT	Wind Turbine
x	produced hydrogen (kg H_2/hr)
y	the capital cost of the electrolyser (£)
ΔP_L	Pressure Difference (Pa)
η	Efficiency
ρ	Density (kg/m^3)
υ	Kinematic Viscousity

1 Introduction

1.1 Impacts of population growth and climate Change on coastal zones

With industrialization and better health care facilities, life expectancy has increased and overall death rate declined. World's population has seen an exponential growth (Figure 1). World population is expected to increase by 2.3 billion, passing from 7.0 billion to 9.3 billion between 2011 and 2050, the (UN-HABITAT, 2011).

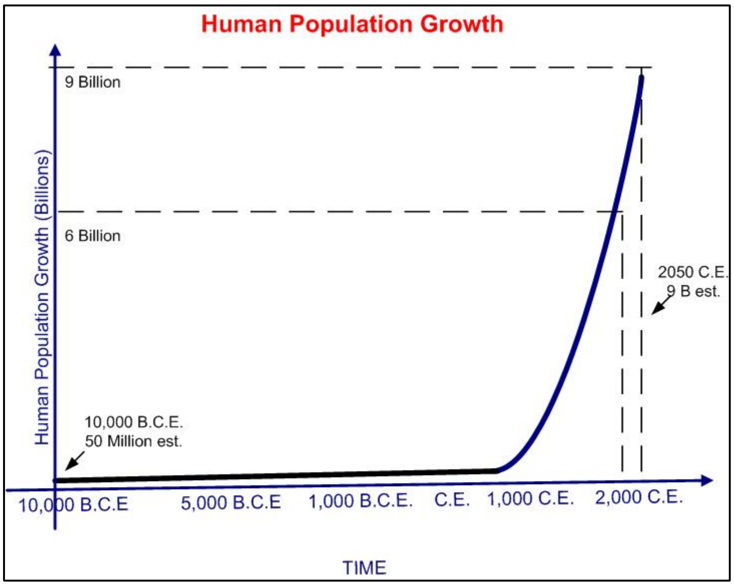

Figure 1: Human of population growth[1].

At the same time, the population living in urban areas is projected to gain 2.6 billion, passing from 3.6 billion in 2011 to 6.3 billion 2050. The urban areas of the world are expected to absorb all the population growth expected over the next four decades. Such population growth has posed a pressure of momentous

[1] Source:http://www.quantrek.org/Population_growth/population%20Growth.htm

scale on ecosystems and our societal institutions and infrastructures (NCADAC, 2013).

An overwhelming amount of evidence exists in scientific literature that increased human activity since industrial revolution (1970) has drastically increased atmospheric concentrations of greenhouse gases (GHGs) - primarily carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and far exceed pre-industrial values determined by ice core data spanning the past 10,000 years (Figure 2). Moreover, global greenhouse gas emissions have increased more than 70% between 1970 and 2010.

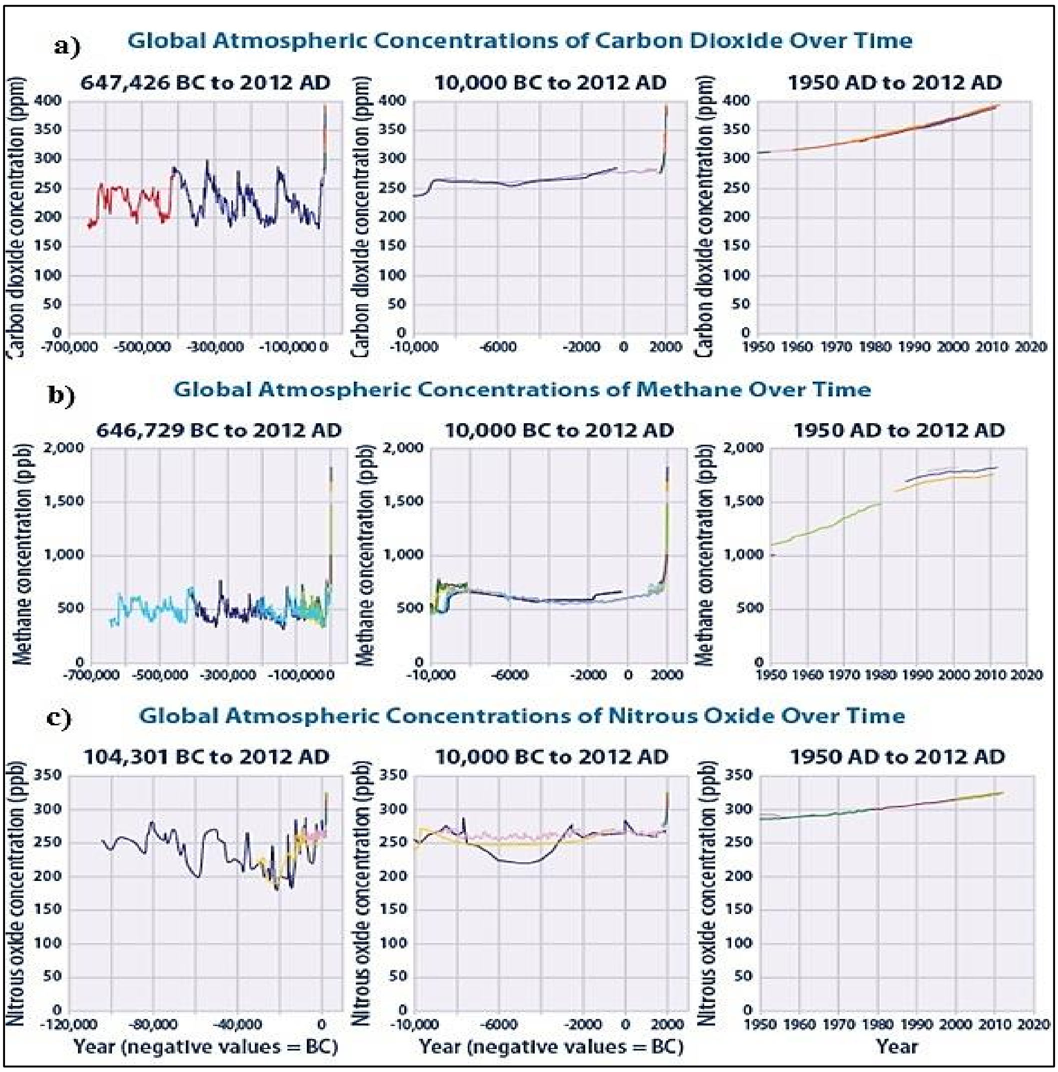

Figure 2: Global atmospheric concentrations of the main Green House Gases (GHGS)[2].

1.2 Coastal areas and coastal cities

Coastal areas are defined as areas between 50 meters below mean sea level and 50 meters above the high tide level, or extending landward to a distance of 100 kilometres from shore, including estuaries, intertidal zones, seagrass communities and coral reefs (UNEP, 2006).

[2] Source : http://www.epa.gov/climatechange/science/indicators/ghg/ghg-concentrations.html.

As of 2008, over half of humanity lives in cities. Humanity today is experiencing a dramatic shift to urban living. A mere 10% of the global population were urban dwellers in 1900, that percentage now exceeds 50% and will rise even more in the next 50 years. The number of megacities (with populations over 10 million) grew from 3 in 1975 to 19 in 2007, and is projected to increase to 27 in 2025 (UN-HABITAT, 2011; UN-Report, 2012). Among the 63 most populated urban areas (with 5 million or more inhabitants in 2011), 39 are located in regions that are exposed to a high risks from flooding, cyclones, and droughts; 72 per cent of those high risk cities are located on or near the coast, and two thirds of them are in Asia (UN-HABITAT, 2011).

Coastal regions harbour a disproportionate amount of the population and contribute greatly to the global economy. Although, they account for only 2 % of the world's total land area but approximately 13% of the world's urban population lives in these zones – with Asia having a higher concentration. By 2025 coastal zones are going to be inhabited by 74% of the world population (Balk et al., 2009) which creates an enormous amount of load on those systems (UN-Report, 2012). Such rapid population growth has posed a pressure of momentous scale on ecosystems and our societal institutions and infrastructure (NCADAC, 2013).

1.3 Challenges or vulnerabilities of coastal zones and coastal cities

Coastal zones are one of the most productive regions of the world both in terms of ecology and economy. Coastal zones include wide range of ecosystems starting from estuaries, wetlands, marshes and intertidal zones that harbours rich biodiversity. Estuarine habitats provide a nursery for many types of the fish we eat. Salt marshes may act to reduce bacterial contamination of runoff and in doing so provide clean water for swimming and surfing; intertidal vegetation draws carbon from the atmosphere (as carbon dioxide) and sequesters it in roots and marsh soils, reducing one of the most abundant greenhouse gases (GHG). Commercial ports and cruise liners operating in coastal zones support tourism and recreational activities that can contribute substantially to national economies.

With sea-level rise, urban areas along the coasts, particularly those in low-elevation coastal zones, will be threatened with flooding and inundation, saltwater intrusion affecting drinking water supplies, increased coastal erosion and reductions in liveable land space. All of these effects will be compounded by other climate impacts, such as increase in the duration and intensity of hurricanes and cyclones, creating extreme hazards for both rich and poor populations occupying low-elevation coastal zones.

The impacts of climate change particularly in the low-elevation coastal zones may be severe (Borges, 2011; Cai, 2011). There is ample evidence for impacts of climate change effects on biodiversity, ecosystem structure and ecosystem services in both terrestrial and marine ecosystems (Scott C. Doney et al., 2012; Staudinger et al., 2012). Changing climate coupled with the impacts of human activity have the potential to dramatically alter coupled hydrologic-biogeochemical processes and associated movement of water, carbon and nutrients through various terrestrial reservoirs and the delivery of dissolved and particulate materials from terrestrial systems into rivers, estuaries, and coastal ocean waters. The potential threats that coastal zones faces include sensitivity to warming temperatures and stratification, altered freshwater exports, nutrient export and eutrophication, hypoxia, and ocean acidification (Cai, 2011; Diaz & Rosenberg, 2008; S. C. Doney, 2010; Howarth et al., 2011).

1.3.1.1 Greenhouse gas (GHGs) and carbon emissions in cities

Cities irrespective of coastal and inland make an important contribution to a nation greenhouse gas (GHG) emissions. Although world’s cities only cover 2 % of global land area, they account for a staggering 70% of greenhouse-gas emissions. Many cities are developing strategies to reduce their emissions (UN-Report, 2012). According to UN-HABITAT report in 2011 (UN-HABITAT,

2011) the factors which mainly influences CO_2 emissions in cities are its location, population, urban form and density and finally the wealth consumption pattern of its residents. Studies conducted in different cities around the world (Kennedy et al., 2009) have shown that power generation for household electricity and transport are major sources of GHGs emissions. In the European Union, energy consumption — power and heat generation and consumption in industry, transport and households — accounts for nearly 80% of GHG emissions (Figure 3). The bigger the city the city the bigger is its GHGs emissions, some studies have established strong relationships between urban transportation energy use and population density (Kennedy et al., 2009; Kenworthy & Laube, 2001).

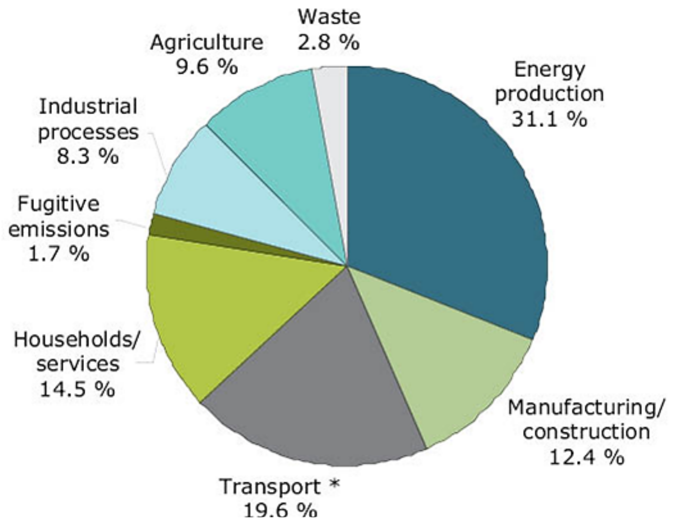

Figure 3: Greenhouse gas emissions in the EU-27 by sector in 2008, and changes between 1990 and 2008 (EEA, 2010)**.**

1.3.1.2 Pollution issues and health hazards in coastal cities

Coastal zones and coastal cities are prone to water borne diseases due to flooding. In general, floods and storms can increase occurrence of waterborne diseases in cities, with cholera and diarrhoea being potentially most problematic. Besides flooding, massive harmful algal blooms (HABs) in coastal areas could also cause problems to human health.

Climate change would also affect air quality, and all diseases resulting from air pollution. As urban population increases so does number of vehicles increases, vehicles are one of the principal emitters of air pollutants and are major contributors to urban air pollution. Road vehicles account for 22.5 % and 21.2 % of total global NO_x and particulate matter (PM) emissions in 2000, respectively (Fulton L & I, 2004), and they are estimated to account for a much larger share of air pollutants emissions in urban areas (Van Aardenne J, Dentener F, Olivier JGJ, & t., 2005). Breathing air that are high in ash, soot, diesel exhaust, chemicals, metals and aerosols (PMs) can potentially cause asthma, heart attacks, strokes and lung cancer (American Lung Association).

1.4 Transport in cities and associated carbon emission and energy consumptions

In a metaphorical way transport in a city can be thought of as veins and arteries of a city. It is important in wealth creation and quality of life of a nation. Transport in cities provides vital networks for both internal and external movements of goods and people. The world's population will reach 9 billion by 2050. The growth of the economy has increased the demand for both passenger and freight transportation. Global passenger mobility is predicted to triple or quadruple by 2050 compared to 2000 (Figure 4).

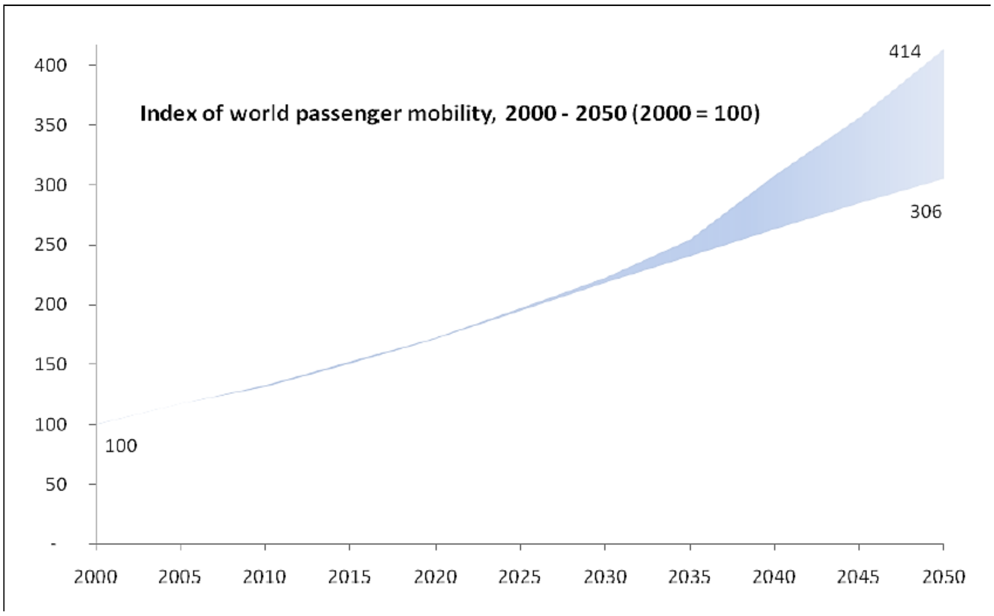

Figure 4: Index of global passenger transport activity 2000-2050 (index of pKm 2000=100)[3].

The relationship between total carbon dioxide emissions, transport carbon dioxide emissions and gross domestic product in world countries from 1975 to 2005 is shown in Figure 5. The blue line shows the development of GDP, the green line shows the development of total CO_2 emissions and the orange line shows the development of CO_2 emissions from transport. Both the emissions and GDP have been growing, but GDP grew faster than the emissions. CO_2 emissions from transport also followed the same general growth pattern (IEA, 2007).

[3] Source: International transport forum calculations were made using MoMo version 2011.

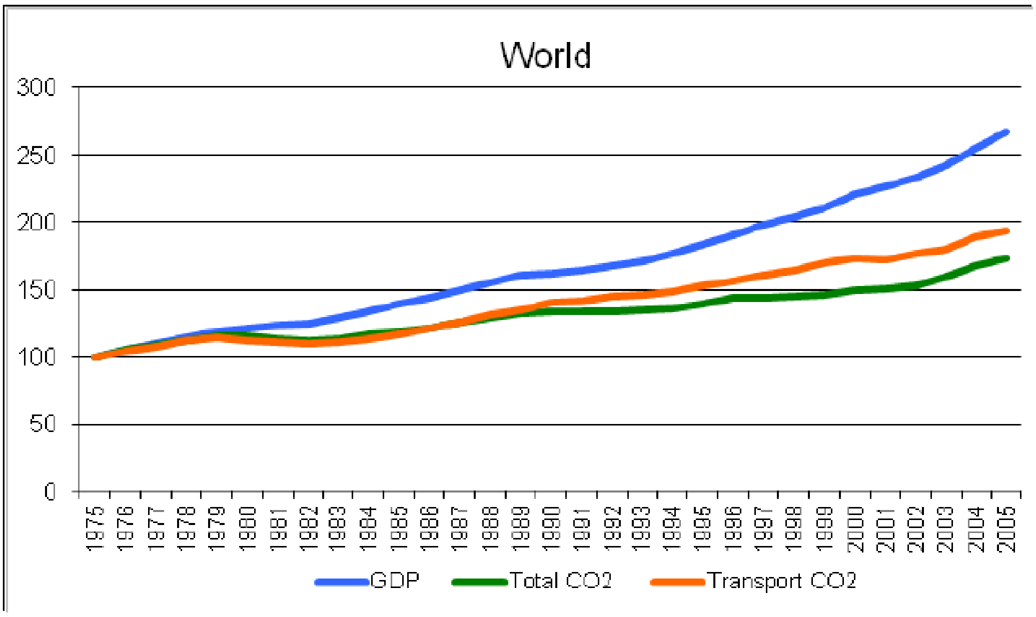

Figure 5: Total CO2 emissions, transport CO2 emissions and GDP (ppp) in world countries in 1975-2005 (1975 = 100) (IEA, 2007).

1.4.1 GHGs emissions from transport

Globally, transportation is responsible for about 23% of total energy-related GHG emissions (UN-HABITAT, 2011)[4]. Road transport alone contributes about one-fifth of the EU's total emissions of carbon dioxide (CO_2), the main greenhouse gas. More than two thirds of transport-related greenhouse gas emissions are from road transport. The breakdown of GHG emissions by domestic transport in UK is shown in Figure 7. About 73% of global transport-related CO_2 emissions in 2007 and 90% of domestic transport-related GHG emissions in the UK (DFT, 2009) were due to road transport, which will also be a major driver of domestic GHG emissions in the newly industrialized economies of China and India.

[4] Source: http://www.unhabitat.org/downloads/docs/GRHS2011-1.pdf

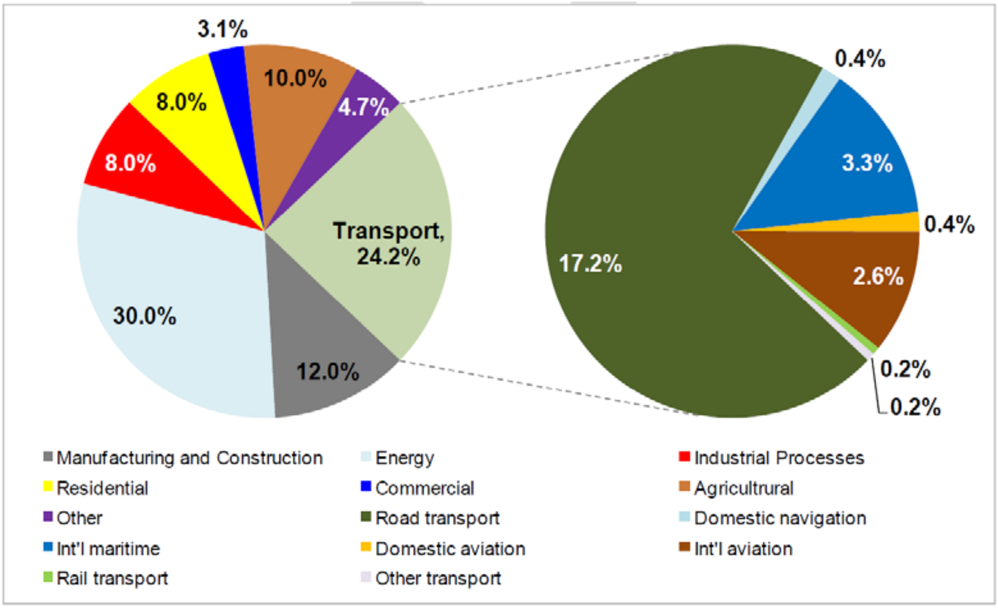

Figure 6: EU27 greenhouse gas emissions by sector and mode of transport, 2007. EU greenhouse gas emissions from transport and other sectors and by mode of transport, million tonnes of CO_2 equivalent, 1990-2000.

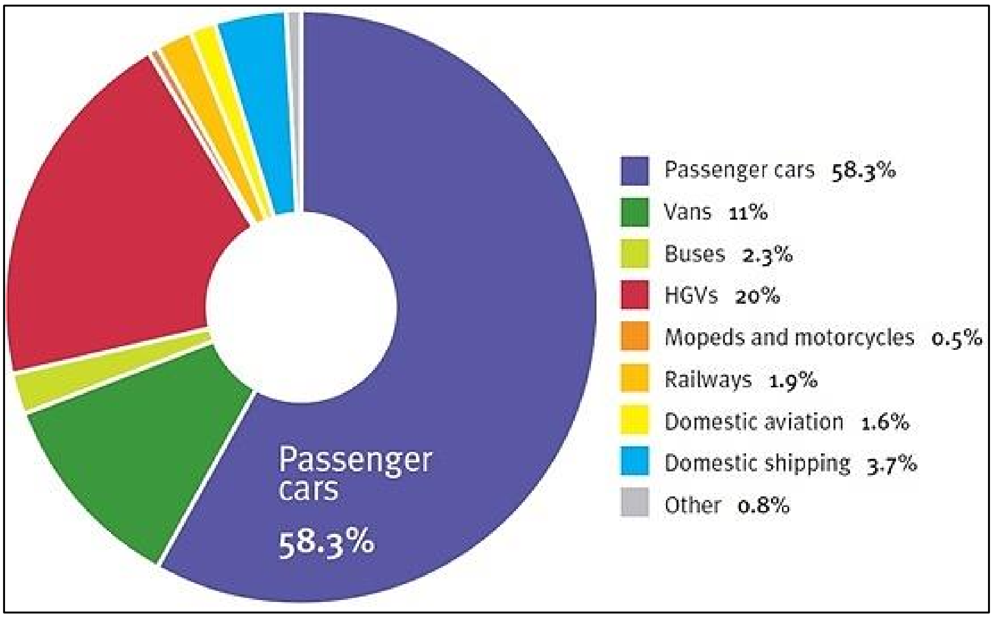

Figure 7: UK domestic transport GHG emissions 2007 excluding travel across borders (DFT, 2009).

1.4.2 Energy consumption in transport

Energy consumption in the transport sector is dominated by road transport, which accounted for 76% of total transport demand in 2010. The Global energy consumption for transport increased by 1.9% per year between 2000 and 2010, increasing from 79.5 EJ to 96.3 EJ in 2010 (Figure 8). Land transport energy consumption is dominated by road transport, which accounts for 76% of energy consumed and is the focus of this report.

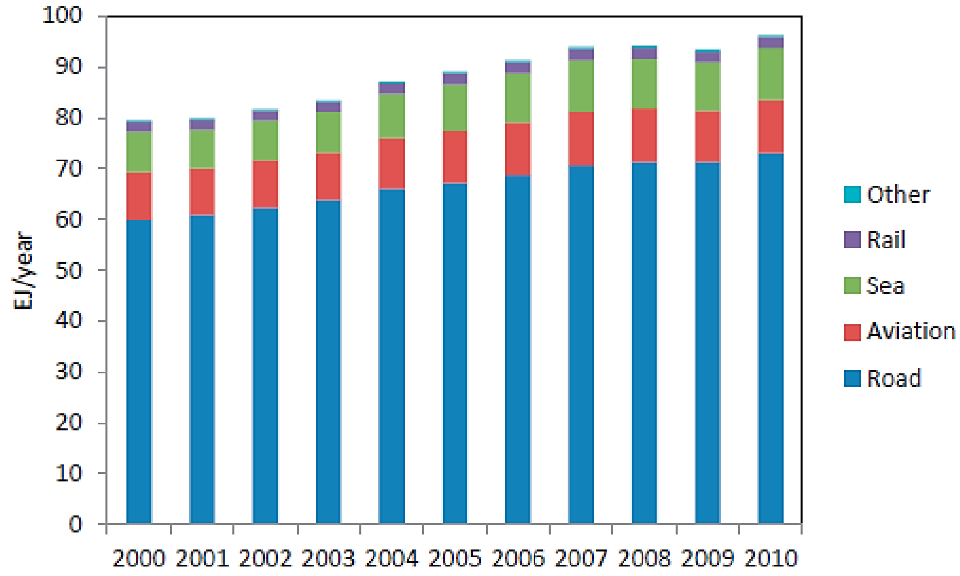

Figure 8: Energy consumptions in transport sector from 2000 to 2010 (IEA, 2013)[5].

1.4.3 Transport in coastal cities

Coastal areas are major centres of economic activity; some of the world's largest ports are located in coastal zones. The marine transportation infrastructure which includes ports and harbours supporting intermodal terminals, ships and barges faces another serious challenge. The expected climate change (intense precipitation and sea level rise); will greatly impact coastal ports and harbour facilities. Higher tides and storm surges from rising seas will affect services for wet and dry docks. Climate change will affect land transportation modes both in coastal. All vehicles that use the highway facilities—passenger cars, trucks, buses, rail and rail transit cars—and pipelines (recognizing that the latter are

[5] Source: http://www.irena.org/DocumentDownloads/Publications/Road_Transport.pdf.

buried underground in many areas) will be either directly or indirectly effected by climate change (TRBS-Special Report, 2008).

To date, little attentions have been paid to the consequences of climate change and weather conditions for the transport sector (Koetse & Rietveld, 2009). Climate changes in some regions may necessitate permanent alterations, roads, rail lines, and airport runways in low-lying coastal areas are highly likely to be relocated. Sustainable measure should be taken in order to protect and maintain coastal zones from immediate threats due to human activity and human indices climate change.

1.5 Seeking a solution: sustainable development

In the background of growing concern over declining ecological trends and the seeming incompatibility of economic and environmental perspectives, people have been on a long journal of seeking for a solution for a more sustainable developing mode. The definition of sustainable development is given as meeting "the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). The comparison between a resource depleting developing mode and a sustainable development is given in Figure 9. The current developing mode is unsustainable by depleting the limited energy resources, while producing a large amount of waste and pollution which have adverse environmental impacts; on the contrary, a sustainable developing mode aims to function as a cycle of energy flow, so that the energy efficiency is relatively higher, and at the same time less adverse output is resulted. The idea of sustainable development provides the base on which the concept of eco-city has emerged. Developing eco-cities is regarded as a mitigation procedure for the climate change and energy shortage faced during the process of urbanization. In particular, developing coastal eco-cities may provide solutions to specific challenges faces by coastal areas, and hence to achieve a sustainable development in these crucial areas.

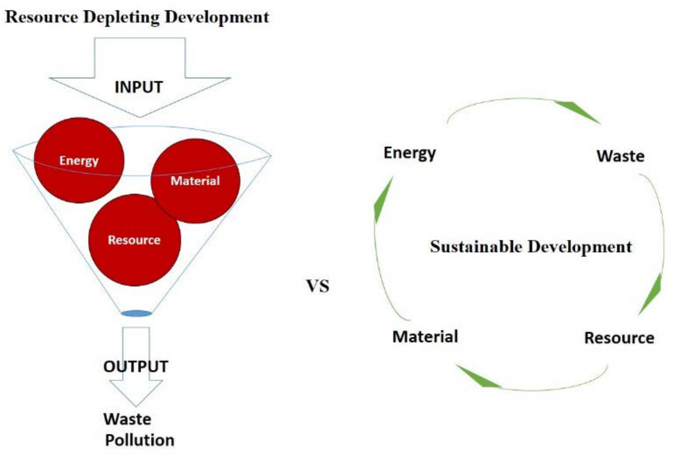

Figure 9: Comparison between two developing modes.

1.5.1 The concept of coastal eco-cities

An eco-city, or a sustainable city, is a term first coined by Richard Register in his 1987 book (Register, 1987). Richard proposed an "eco-city" as a city like a living system with a land use pattern that supports the healthy anatomy of the whole city, enhances biodiversity, and makes the city's functions resonate with the patterns of evolution and sustainability (Wong & Yuen, 2011). Ever since it has been proposed, the term "eco-city" has been gaining a popularising, thanks to Register, Engwicht, and Urban Ecology[6] along with those thinkers and writers many decades ago whose ideas were precursors to this concept (Roseland, 1997).

There is no (and perhaps should not be any) single accepted definition of "eco-cities". The eco-city concept is diverse, and has been strongly influenced by other movements regarding sustainable development ever since it was first proposed. The dimensions of the eco-city concept mainly include appropriate technology, community economic development, social ecology, the green movement, bioregionalism and sustainable development (Roseland, 1997).

Following the main idea from different sources of information regarding the crucial elements for an eco-city, here the definition of the "eco" part adopts that

[6] Urban Ecology: a non-profit organization to "rebuild cities in balance with nature" founded by Richard Register and a few friends in Berkeley, CA, in 1975 (Roseland, 1997).

with a double meaning as pointed out by the World Bank (Suzuki, Dastur, & Moffatt, 2010), i.e. “eco” stands for both ecology and economy (represented by the symbol “ECO^2”). The principle is that the economic development of the city should minimize any adverse environmental influences to maintain a balance between urbanization and the environment. A definition sketch showing this definition involving both ecology and economy is demonstrated in Figure 10. Some global issues which we are facing today as listed in Figure 10 and they all fit in the two main aspects, i.e. economy and ecology.

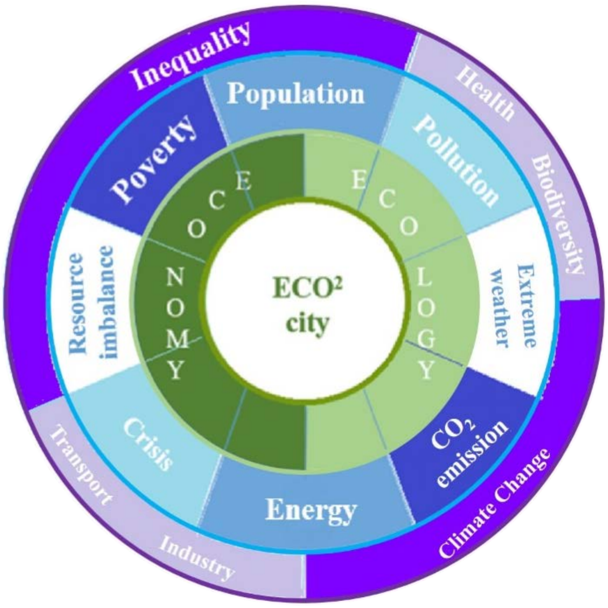

Figure 10: Definition for ECO^2.

Overall, a global eco-city framework and associated standards are being formed quickly. Several eco-cities initiatives are mentioned in “Eco-city Planning: policies, practice and design” (Wong & Yuen, 2011), which include but are not limited to, Stockholm in Sweden, Tianjin in China, Singapore, Yokohama in Japan, Brisbane in Australia and Auckland in New Zealand. Many more discussions on other eco-cities worldwide can be found in various studies (Joss, 2010; Joss, Tomozeiu, & Cowley, 2011). In addition, there are various award schemes to increase the implementation of eco-city constructions, examples are the Aberdeen EcoCity Awards and European Green Capital awards. The winning cities from the European Green Capital awards are Stockholm in 2010, Hamburg in 2011, Vitoria-Gasteiz in 2012, Nantes in 2013, Copenhagen in 2014 and Bristol in 2015. It can be found that one important factor of almost all these winning cities as role models is their low CO_2 emission resulted from low independent on fossil fuels in transport.

Following the previous discussion on eco-city, a coastal eco-city, therefore, is a city seeking ecologically sound economic development that is located in coastal areas. In some extend, seeking a sustainable developing mode in coastal cities may be even more crucial. Among the ten principles to create ecologic cities given by Urban Ecology (Ecology, 1996), it has been pointed out that “restore damaged urban environments, especially creeks, shore lines, ridgelines and wetland”. There are various reasons for this. First, as mentioned before, urbanisation probably is under a more advantageous situation in coastal areas and hence the associated problems with rapid urbanisation are more severe in these regions. Second, coastal areas are always very important in both economic and political meanings for their own country. Third, coastal cities have specific threats compared with other inland cities and these threats may in return significantly influence the inland cities, e.g. subsiding due to the sea level rising as a consequence of global warming.

As described previously, today’s cities particularly coastal cities are facing an insurmountable amount of pressure due to rapid population growth and climate change. Under such scenarios a new model for cities is increasing developing-the concept of eco-city. The goal is to reduce the impact on the environment, and for that to happen, three major challenges needs to be addressed: 1) Major transformation of building infrastructure; 2) radical changes in our transportation system and 3) new ways to implement to supply electricity in our cities.

Transport as described previously provides access; to work, education, goods and services and meeting place in all kinds of city. In order to make a city truly eco-friendly strategies for sustainable transport needs clearly defined and we need to clearly understand the technology and policy options.

1.5.2 Eco-friendly transport with emphasis on coastal cities

There are many definitions of sustainable transport, and of the related terms 'sustainable transportation' and 'sustainable mobility (Litman, 2009). The European Union Council of Ministers of Transport defines a sustainable transport system as a system that (Source: Wikipedia)

- *"Allows the basic access and development needs of individuals, companies and society to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations".*
- *"Is Affordable, operates fairly and efficiently, offers a choice of transport mode, and supports a competitive economy, as well as balanced regional development".*
- *"Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses non-renewable resources at or below the rates of development of renewable substitutes, while minimizing the impact on the use of land and the generation of noise".*

Sustainable transport aims to have a low impact on the environment, provides for basic social needs and supports the economic functioning of the community.

Sustainable transport encourages breaking the habit of driving private motor vehicles and encourages alternatives that include walking, cycling and public transport. It proposes ideas for accommodating a greater share of private and public transport vehicles that have a reduced ecological footprint, including vehicles fuelled by renewable resources. Recognizing that private motor vehicle transport is likely to remain the dominant mode of the sustainable transport system, switch to cleaner cars and alternative fuels, effective mobility management, rapid transit, fare sharing and integration of different transport modes are some of the ideas of sustainable transport.

This report explores how such goals in transport sector can be achieved in a coastal city by using renewable energy, alternative fuels and integration of different modes of transport.

2 Technology

2.1 Renewable energy

The concept of renewable energy is proposed as a solution to the issue of the limited resources of fossil fuels (coal, natural gas and petroleum) and nuclear power (uranium and thorium). The definition for renewable energy is given as "a flow of energy that is not exhausted by being used" (Sørensen, 1991).

Nowadays, the need to evaluate the sufficiency and deployment of renewable energies in an economic manner has been growing continuously This is a result of the rapid speed of urbanisation and its adverse effect on city transportation, including fossil fuel depletion and environmental impacts such as global warming. As pointed out by Koppen (Van Koppen, 1981), the world has become highly dependent on energy and raw materials, while at the same time the large number of population is to draw on the finite resources in an "*unacceptably strong and fast way, at the same time creating a most difficult waste problem*". The world energy consumption is estimated to rise considerably over the next decades, and the energy sector is forced through a renovating process, which sees an opening towards renewable energy that is environmentally friendly and sustainable. In the application of renewable energy schemes to a coastal city, the first question that needs to be answered is that about the availability of renewable resources and the techno-economic viability of utilising them.

2.1.1 Available forms

Following the definition given above, there are a number of fundamental sources of energy on earth that can be regarded as renewable. These include solar radiation, geothermal heat and earth spanning combined with gravitational forces of the Moon-Earth-Sun planetary system (Dinçer & Zamfirescu, 2011). Among these, solar energy is commonly regarded as a primary renewable energy since it can be directly re-radiated into space in the form of heat. In addition, the indirect forms of solar energy also have the attribute of being renewable; these forms include wind, waves, tidal, hydro, geothermal, ocean thermal, and biomass energy (Dinçer & Zamfirescu, 2011). A general classification is given below Figure 11. In the following, several most commonly used types are discussed; their generation, present and future developing state with a touch of economic evaluation are mentioned.

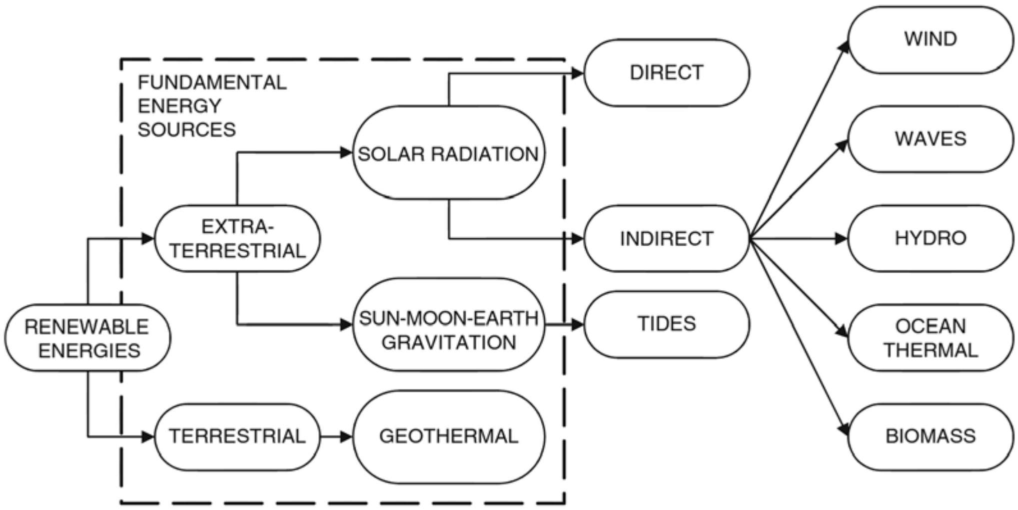

Figure 11: Classification of renewable energies (Dinçer & Zamfirescu, 2011)**.**

2.1.2 Solar energy

2.1.2.1 Production

The sun's radiation can be used to produce heat using the solar architecture; in addition, it can be used to produce electricity directly by using photovoltaic (PV) cells, or indirectly by using solar heat in a thermal heat cycle (Bartels, Pate, & Olson, 2010).When converted to electrical energy, it can be transmitted to the electric grid, which can then be consumed or stored (e.g. viz. electric batteries, or converted into hydrogen through water electrolysis). The path for the use of direct solar radiation is outlined in Figure 12 (Dinçer & Zamfirescu, 2011).

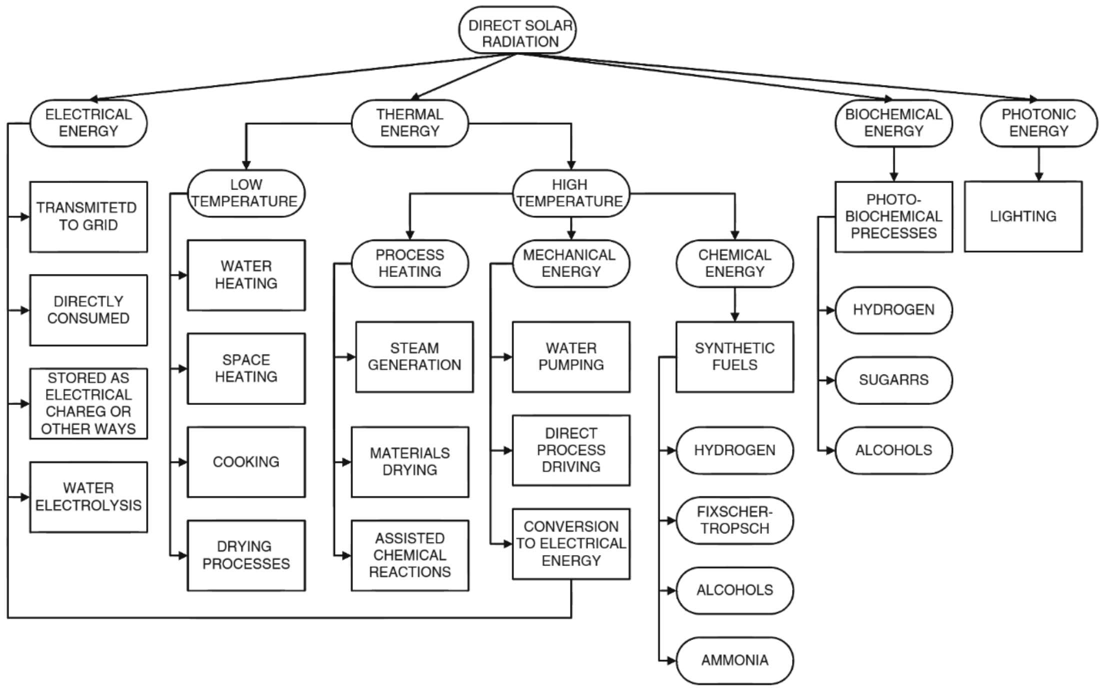

Figure 12: Conversion paths of direct solar radiation with engineered systems (Dinçer & Zamfirescu, 2011).

2.1.2.2 Current state

Use of solar energy has been seeing a rapid growth around the world. In 2011, total global solar PV capacity increased by 75% to about 69.2 BW, and on average could produce 85 terawatt hours (TWh) of electricity every year ("Global Market Outlook for Photovoltaics until 2016," 2012). The solar energy is now the third most important renewable source in terms of globally installed capacity. Two examples for available technologies are given below:

- **Photovoltaic electrolysis** is fast developing technology that converts solar radiation directly into electricity based on photovoltaic panels (PV). Among all kinds of solar cells being produced today, the most common one are silicon based. The overall efficiency of conversion may range from 10 to 30%, e.g. low for amorphous silicon, medium for crystalline silicon and high for gallium arsenide (Sørensen, 1991). Figure 13 shows a typical PV park which is a combination of a group of photovoltaic panels.

Figure 13: An example of a PV park (Fernández-Pacheco, Molina-Martínez, Ruiz-Canales, & Jiménez, 2012).

- **Concentrated solar energy** is a technology that uses lenses or mirrors to concentrate a large area of sunlight into a small beam on a receiver to heat the latter to a high temperature. The temperature difference between the receiver and the ambient temperature then produces a thermodynamic power cycle, which is next used for power generation. This technology can use either a central receiver system or a distributed system using many concentrators.

2.1.3 Wind energy

2.1.3.1 Production

Wind energy is an indirect form of solar energy. There are various ways of collecting and converting it into other types of useful energies, for example, wind turbines to produce electricity, windmills to make mechanical work, wind pumps for pumping water or sails to propel ships (Nikitakos, 2012). The conversion path of wind energy is outlined in Figure 14 (Dinçer & Zamfirescu, 2011).

The primary use of wind energy is to install wind turbines for the aim of electricity producing. Figure 15 demonstrates the main components of a typical wind turbine. The wind energy is first transformed into mechanical energy which rotates the turbine; the mechanical energy is then stored in devices which can retrieve the mechanical energy, such as hydro-storage, flywheels or compressed air; finally the mechanical energy is converted into electricity using appropriate electric generators. A large group of individual wind turbines is typically brought together to form a wind farm (Bartels et al., 2010). The current state of the technology regarding wind turbines is mentioned in the following section.

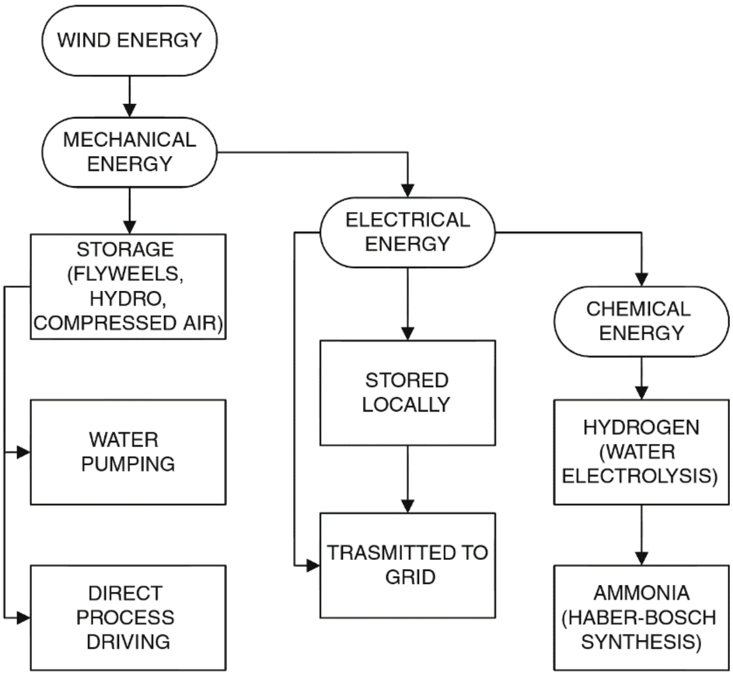

Figure 14: Conversion paths of wind energy (Dinçer & Zamfirescu, 2011).

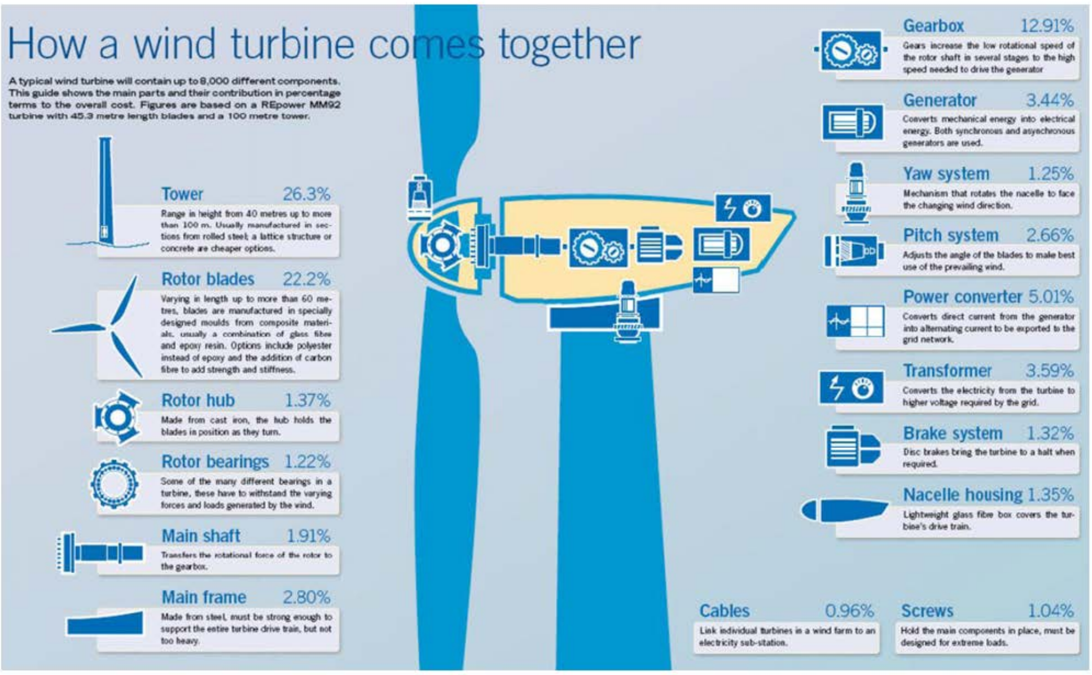

Figure 15: Main components of a wind turbine and their share of the overall cost (Shafiullah, M.T. Oo, Shawkat Ali, & Wolfs, 2013).

2.1.3.2 Current state

The advantages of using wind power, as an alternative to fossil fuels, include worldwide accessibility, zero greenhouse gas emissions during operation and little land occupation. Total global wind power capacity was 238 GW at the end of 2011, which saw an increase of over 20% from 2010 (Olivier, Peters, & Janssens-Maenhout, 2012). The largest wind power market is now located in China, where new infrastructure installations and 17,600MW of new wind capacity were added in 2011.

Installation of wind turbines should be designed with the consideration of the regional and seasonal dependence of wind energy. Figure 16 presents the averaged wind output and total demand following different months in a year in the UK (Change, 2011). It is reported that, if neglecting radial and rotational flows and only considering flow in one single direction to be dominant, then wind turbines will have a fundamental efficiency limit of 16/27 for a fixed turbine area (Sørensen, 1991). In practice, although fixed blade-pitch and fixed rotational velocity reduce the average efficiency, the efficiency value at around 35% is realistic for locations with good wind conditions (Sørensen, 1991). Nowadays many wind turbines are installed offshore, especially for coastal or port areas, to deal with the problem of land expansion (Nikitakos, 2012). Figure 17 depicts an offshore farm of wind turbines. If wind turbines are designed to extract power from an area larger than their corresponding dimensions, a problem that might appear is interference between neighbouring turbines.

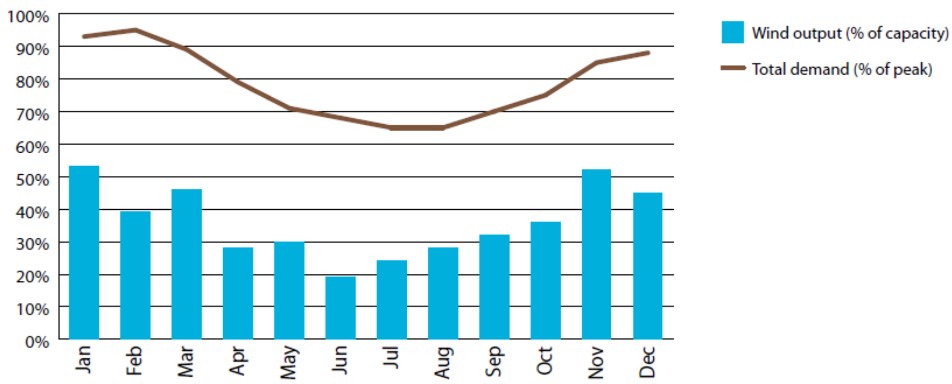

Figure 16: Seasonality of wind generation versus seasonality of demand[7].

Figure 17: Wind turbines (Mostafaeipour, 2010).

[7] Source: CCC calculations based on modelling by Pöyry.

Note: Based on observed patterns in 2006, 2007, 2008 and 2009 (averaged) and for indicative 2030 wind deployment and demand.

2.1.4 Wave energy

Wave energy, a concentrated form of solar energy, can also be used to produce electricity. A wave carries both kinetic energy and gravity energy; its strength roughly depends on two parameters, namely the wave height (*H*) and period (*T*). The energy of waves is proportional to H^2 and *T* (Cruz, 2008).

2.1.4.1 Production

Ocean waves can be formed by surface winds, tides and ocean currents. Machinery used to extract energy is called wave energy converter (WEC). A one WEC may produce power up to 2MW[8]. There are different types of WEC, for instance, attenuator, point absorber, oscillating wave surge generator, oscillating water column, overtopping/terminator device, submerged pressure differential, etc. An example of offshore energy converter can be seen in Figure 18. Wave energy can be collected with floating bodies that execute elliptic movement under the action of gravity and wave motion. For instance a buoy-type wave energy converter, as shown in Figure 19 (Dinçer & Zamfirescu, 2011) works by discharging the high-pressure liquid into a low-pressure reservoir to generate shaft work that turns an electric generator to produce electricity.

Figure 18: Offshore wave energy generator[9].

[8] Source : http://www.40southenergy.com

[9] Source : http://www.greenlivinganswers.com/archives/156.

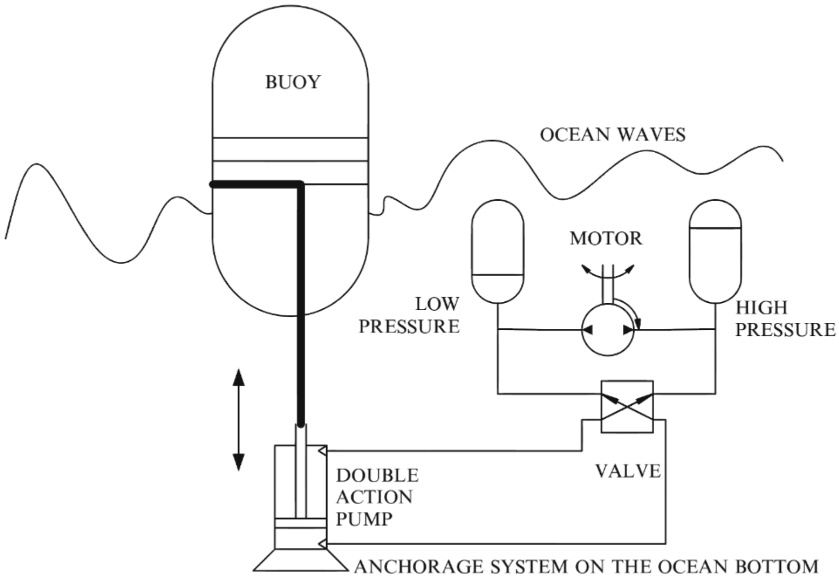

Figure 19: Principle of operation of buoy-type ocean wave energy conversion system (Dinçer & Zamfirescu, 2011).

2.1.4.2 Current state

Another promising type of renewable energy is the wave energy. One typical feature of wave energy is that, once created, it can travel thousands of kilometres with little energy loss. Areas with high wave energy include the western coast of Europe, the southern parts of South America and the Antipodes (Clément et al., 2002).

The intensive research in the use of wave energy set off after the dramatic increase in oil prices in 1973. Although it has received some doubts in the past, constant research in more than three decades has led to a closer possibility for commercial exploitation of wave energy (Clément et al., 2002). According to the UK TINA report (Group, 2012), designs for wave energy have diverse concepts including oscillating water columns, overtopping devices, and point absorbers. However, currently only two types of technologies have been deployed at a full scale demonstration.

2.1.5 Tidal energy

Tidal energy, also known as "lunar energy", is a unique type of hydro-power, derived from the combined effect of the planet's spinning motion and the gravitational forces associated with the earth-moon and earth-sun system. One unique advantageous feature of tidal energy is its accurate predictability associated with the regular movement of the sun and the moon.

2.1.5.1 Production

A diurnal tidal effect is resulted from the moon's gravitational pull on the oceans under the earth's rotation. There is a combined action of gravitational and centrifugal forces (Dinçer & Zamfirescu, 2011). The tides formation is explained in Figure 20.

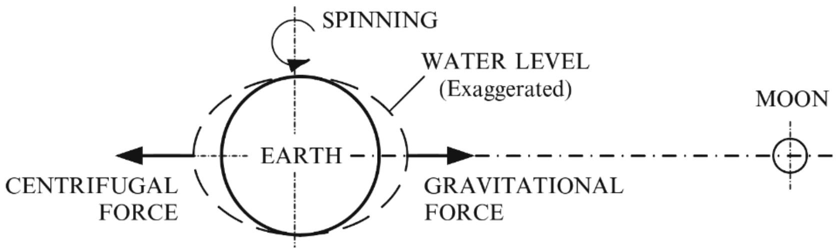

Figure 20: The formation of tides (Dinçer & Zamfirescu, 2011)**.**

The device used to harvest tidal energy is called tidal energy convertors (TEC[10]). Different types of such devices include horizontal axis turbine, vertical axis turbine, oscillating hydrofoil, enclosed tips (venturi), Archimedes screw and tidal kite. Tidal energy can be used to produce electricity in mainly two ways:

- **Tidal impoundment (barrage) system**, which impounds water to create a difference in water level. Then the kinetic energy of the elevated mass of water can be converted by the appropriate device into electricity. Figure 21 shows an example of a tidal barrage system, which uses the energy of an incoming rising tide.

[10] Source: http://www.emec.org.uk/marine-energy/tide-devices.

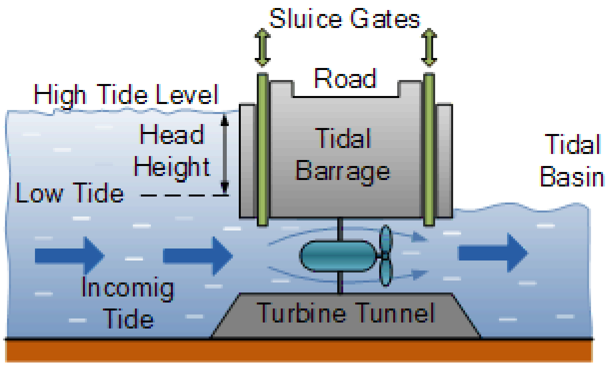

Figure 21: Tidal Barrage Flood Generation system[11].

- **Ocean current-harvesting systems** extract the water current's energy, which is generated by the action of tides, and use this energy for electricity generation.

2.1.5.2 Current state

The UK TINA report (Group, 2012) has mentioned that by year 2012 only four technologies of using tidal energy had been deployed at full scale demonstration. Tidal devices have converged to a greater extent with most designs now based around horizontal axis turbines, which share some similarities to wind turbines. There are some earlier stage designs still looking at the potential for vertical axis turbines, hydrofoils and Venturi-effect devices, in some case for niche applications. As mentioned in "*Wave and Tidal Energy in the UK - Conquering Challenges, Generating Growth*" (Krohn et al., 2013), the past year (2012) has seen a significant increase in the development of tidal energy industry, e.g. there have been 12 large-scale prototype devices deployed or installed around the UK, facilitated by the support from government and policy makers.

2.1.6 Geothermal energy

2.1.6.1 Production

The ground stores thermal energy originating from the creation of the planet and the natural decay of minerals (Nikitakos, 2012). Geothermal heat can be

[11] Source: http://www.alternative-energy-tutorials.com/tidal-energy/tidal-barrage.html.

converted to electricity through appropriate heat engines. Geothermal energy is available in some regions of the earth's surface at temperature levels in the range of about 35° to 500°, but the majority of the geothermal places provide temperature levels up to 250° (Dinçer & Zamfirescu, 2011). Figure 22 gives different types of geothermal fields and their utilizations.

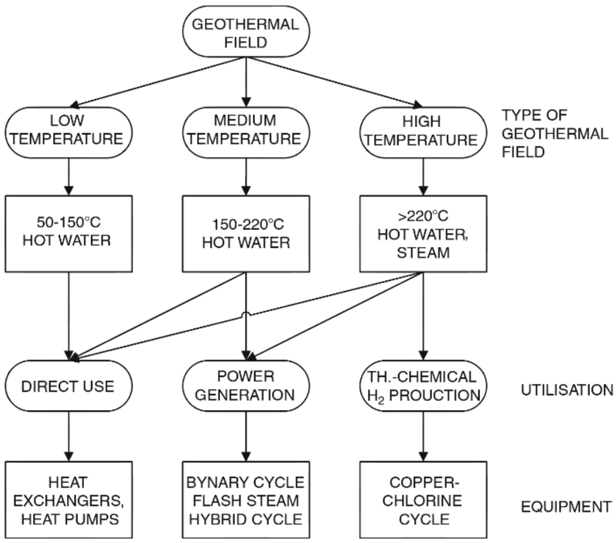

Figure 22: Classification of geothermal fields and utilization of geothermal energy (Dinçer & Zamfirescu, 2011).

2.1.6.2 Current state

Figure 23 shows the division of the global use of geothermal energy in terms of heating applications (Lund, 2004). It has been pointed out that current use of geothermal energy is mainly reservoir-based and non-renewable. The efficiency of geothermal energy is dependent on the conversion of the straight thermodynamical considerations (Sørensen, 1991). As a source of heat, the limit of geothermal energy conversion is determined by the Carnot factor. A general picture of the thermodynamic limits of geothermal energy conversion can be obtained by assessing the range of the Carnot factor for geothermal reservoirs (Dinçer & Zamfirescu, 2011).

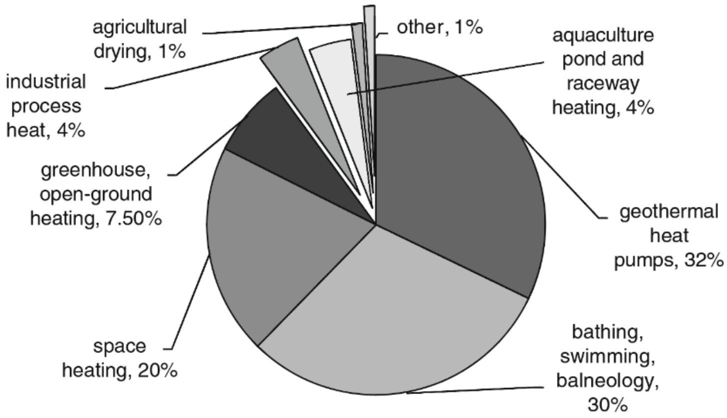

Figure 23: Global use of geothermal energy for heating applications (Lund, 2004).

2.1.7 Future of renewable energies

Renewable energies are now globally accepted as a promising way for transport decarbonisation and are receiving increasing interest. The growing trends in renewable energy consumption in different locations worldwide are demonstrated in Figure 24 (Sadorsky, 2011), from which a global increase of renewable energy consumption is seen, with a steady increase of a faster speed in Europe.

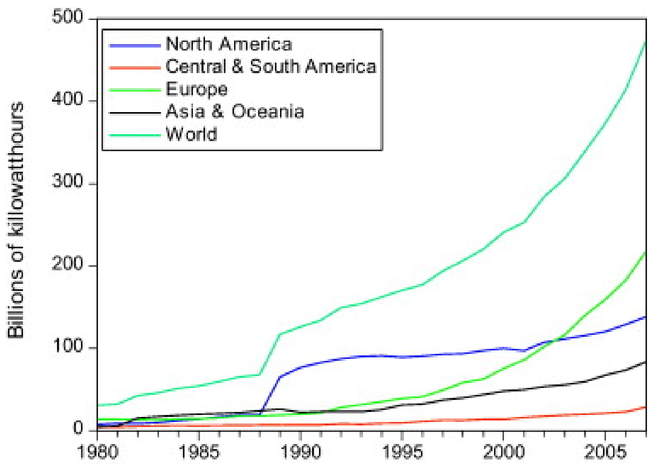

Figure 24: Trends in renewable energy consumption in terms of various locations (Sadorsky, 2011).

According to the REN21 report ("Renewables 2012. Global Status Report.," 2012) on renewable energies status for 2012, by the end of 2011, total global renewable power capacity had exceeded 1,360 GW, supplying approximately 8.5% of all energy and 20.3% of electricity worldwide. This shows an increase of 8% in 2011 over the previous year. The same report has also pointed out the trend the share of renewable energy sources is increasing at a constantly growing rate. The global share was doubled from 0.5% to 1% from 1992 to 2004, while it took only half of the same period for another doubling from 1% to 2.1% (BP, 2012). This trend is going to continue with the increasing awareness of global CO_2 emission impacts and associated policies. As indicated by Figure 25, an increase of the capacity of electricity generation in all kinds of renewable energies is expected in the next two decades, with the power of electricity generation from wind and solar to increase approximately 1200BKW and 180BKW, respectively.

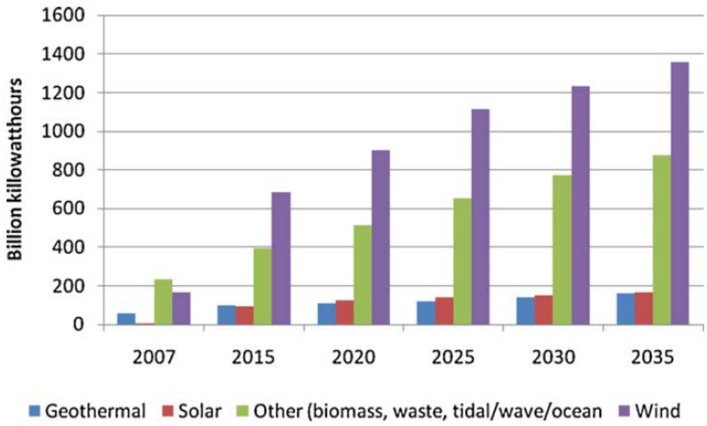

Figure 25: World net renewable electricity generation projects[12]

Renewable energies can be used to produce electricity to be used in transport. One advantage of using these electricity is that, when abundant, the energy generated can be stored in both central or distributed stationary hydrogen stations and mobile energy carriers, for example, hydrogen fuel cells. The primary advantage of using renewable energy in transport sector is mainly reflected by the mitigation of CO_2 emission and hence reducing the adverse environmental impact. The availability potential and the role of reducing carbon dioxide

[12] Source: US EIA (http://www.eia.doe.gov/oiaf/ieo/) appendix H.

emission for each type of renewable energy mentioned above are discussed here respectively.

First, the trend of investment in solar-electric technology and its consequent CO_2 mitigation is shown in Figure 26. One can clearly observe an increase in both the investment as well as the amount of emissions saved per annum.

Second, for the wind energy, the amount of global wind energy generation from year 2000 to 2016 is given in Figure 27, from which a steady rapid increment of energy generation is observed in the past and this trend is anticipated to continue in the future. In addition, the "20% Wind Energy by 2030 - Executive Summary" by The U.S. Department of Energy has determined the target of supplying 20% of U.S. electricity from wind by 2030 (known as "the 20% Wind Scenario"), which would avoid a cumulative total of 7,600 million metric tons of CO_2 emissions by 2030 (Figure 28), among which 825 million metric tons is in the annual electric sector.

Last but not least, as for wave and tidal energy, the UK TINA report (Group, 2012) has mentioned that, the feasibly exploitable resource by 2050 could deliver around 40-50TWh/year of electricity for wave and 20-30TWh/year for tidal (although estimates vary significantly). This can be compared to the current UK electricity consumption of around 360TWh/year and could meet over 10% of expected 2050 total UK electricity needs. The projection of the role of applying wave and tidal energy regarding decreasing CO_2 emission is given in Figure 26.

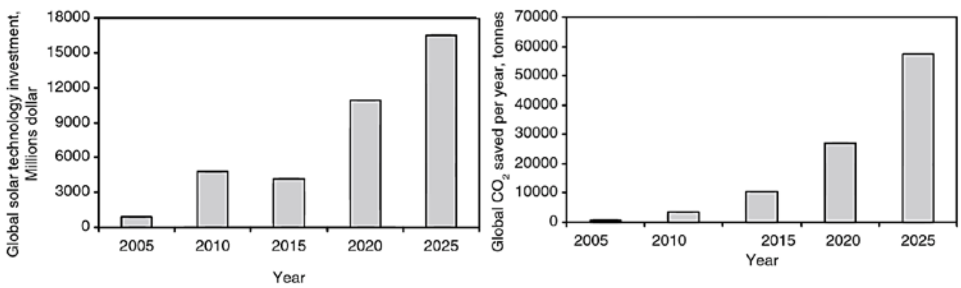

Figure 26: Predictions of solar-electric technology investment and the resulting CO_2 mitigation (Dinçer & Zamfirescu, 2011).

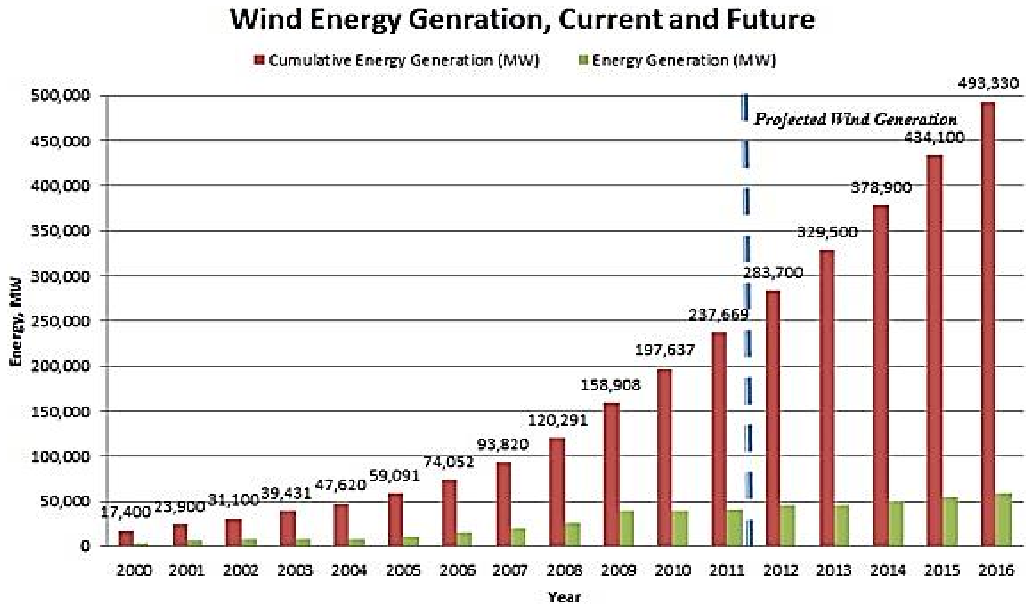

Figure 27: Global wind energy installed capacity, current and projected (Shafiullah et al., 2013).

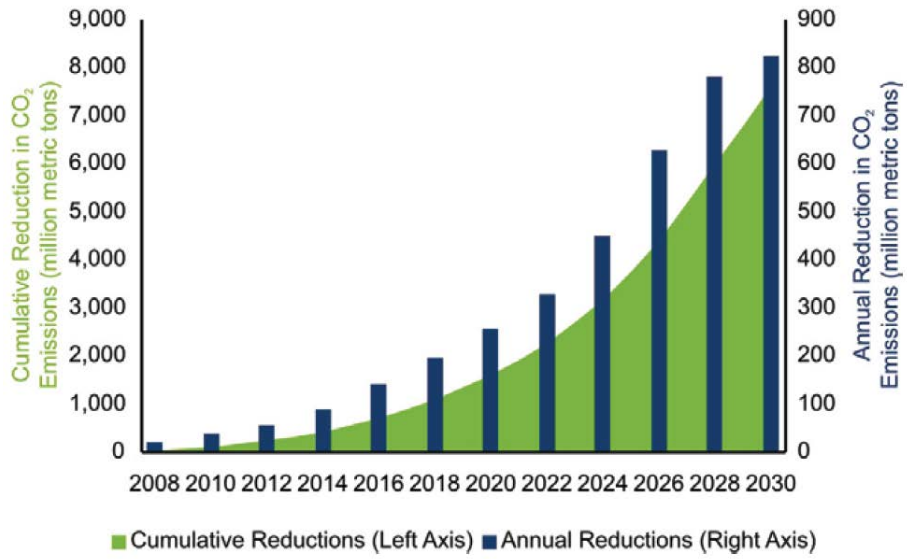

Figure 28: Cumulative reduction in CO_2 emissions annually through the years 2008 to 2030 (Energy, 2008).

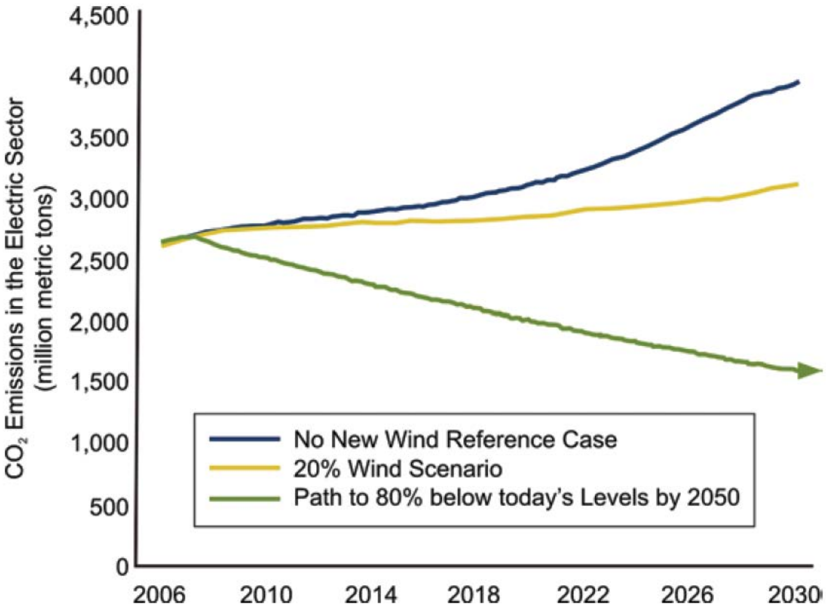

Figure 29: CO_2 emissions from the electricity sector annually through the years 2006 to 2030 (Energy, 2008).

Table 1: CO_2 displaced by wave and tidal sector in 2017 and 2020 under two deployment scenarios (Krohn et al., 2013).

Scenario	Year	Cumulative Capacity Deployed (MW)	CO_2 Displaced (tonnes/year)
Expected Deployment	2017	59	78,000
	2020	130	171,400
Viable Projects	2017	120	158,200
	2020	340	448,300

2.2 The hydrogen technology

2.2.1 Introduction

The word "hydrogen", originating from the Greek words "hydro" and "genes" combined into one, has the meaning of "water generator". The name of hydrogen was given by Antoine Lavoisier in 1783 (Stwertka, 2002), who found that by burning hydrogen water was produced. In fact, the hydrogen element was first identified by Henry Cavendish in 1766 (Emsley, 2011). Hydrogen is the most abundant chemical element (represented by the symbol H) in the world, consisting over 70% of the total amount of chemical elements in the universe. However, pure hydrogen is relatively rare. For example, only around 5.5×10^{-3} % of the total atmosphere on the Earth is hydrogen gas (Mackenzie & Mackenzie, 1998), which is composed by two hydrogen atoms joined together (represented by the symbol of H_2).

With issues associated with the worsening of global climate as well as increasing urbanisation, people have been seeking new and clean energy to replace the conventional fossil fuels to satisfy the energy needs for the future generations in a sustainable way. One attempt was to use hydrogen as an energy provider. This element can be used as an energy carrier, as it allows electric energy to be converted and stored, and later, used by vehicles. There are several existing examples and pilot projects of a hydrogen-based energy system. In particular, the distribution of hydrogen to be applied in transport is tested in many countries, including the UK, the US, the Netherlands, Germany, China, etc.

2.2.2 Hydrogen energy system

The life cycle of using hydrogen as an energy provider can be described as three stages: hydrogen production, distribution (transport and storage) and utilisation. Figure 30 shows a schematic diagram of the hydrogen energy system. A brief introduction of each section is given as follows.

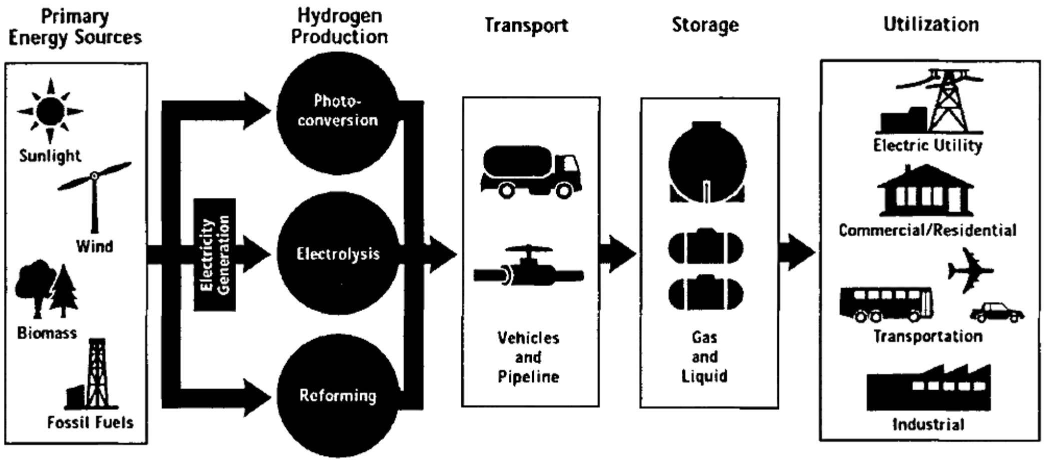

Figure 30: Hydrogen energy system[13].

2.2.2.1 Production of hydrogen

Hydrogen can be produced from primary energy resources through different processes, including reforming of fossil fuels or biomass, electrolysis and photo-conversion. A summary of various hydrogen production technologies is given in Table 2. These technologies are currently in different stages of development. In general, generation of hydrogen through fossil fuels is in a relatively more mature stage for commercial usage than the others (U. K. Mirza, Ahmad, Harijan, & Majeed, 2009). The process of generating hydrogen through electrolysis is also relatively mature and allows hydrogen to be produced in large quantities (Kothari, Buddhi, & Sawhney, 2008). Comparison between the different production methods regarding environmental impact and economic efficiency can be found in various studies (Barreto, Makihira, & Riahi, 2003; Fayaz et al., 2012; Kothari et al., 2008; Ozbilen, Dincer, & Rosen, 2013). Out of all available technologies for hydrogen production, three are discussed below. These are the

[13] SOURCE: National Renewable Energy Laboratory, Hydrogen Program Overview, DOE/GO- 10095-088 (Washington, D.C., 1995), 2.)

two main technologies, i.e. fossil fuel reforming and electrolysis, and a relatively new technology - hydrogen generation through photolytic processes.

Table 2: Technology summary table, adopted from (Holladay, Hu, King, & Wang, 2009).

Technology	Feed stock	Efficiency	Maturity
Steam reforming	Hydrocarbons	70-85%	Commercial
Partial oxidation	Hydrocarbons	60-75%	Commercial
Autothermal reforming	Hydrocarbons	60-75%	Near term
Plasma reforming	Hydrocarbons	9-85%	Long term
Aqueous phase reforming	Carbohydrates	35-55%	Med. term
Ammonia reforming	Ammonia	Not available	Near term
Biomass gasification	Biomass	35-50%	Commercial
Photolysis	Sunlight + water	0.5%	Long term
Dark fermentation	Biomass	60-80%	Long term
Photo fermentation	Biomass + sunlight	0.1%	Long term
Microbial electrolysis cells	Biomass + electricity	78%	Long term
Alkaline electrolyser	H2O + electricity	50-60%	Commercial
PEM electrolyser	H2O + electricity	55-70%	Near term
Solid oxide electrolysis cells	H2O + electricity + heat	40-60%	Med. Term
Thermochemical water splitting	H2O + heat	Not available	Long term
Photo-electrochemical water splitting	H2O + sunlight	12.4%	Long term

On average, about 1.37×10^9 m^3 hydrogen is produced daily worldwide, 99% of which is produced from fossil fuels, such as natural gas reforming and coal gasification (U. K. Mirza et al., 2009). The chemical equations for hydrogen generation through natural gas reforming are as follows (De Souza & Silveira, 2011):

$$CO_4+H_2O \text{ (steam)} \rightarrow 3H_2+CO \qquad 2.1$$

$$CO+H_2O \text{ (steam)} \rightarrow CO_2+H_2 \qquad 2.2$$

The efficiency of this method is about 70-80% (Serrano, Rus, & Garcia-Martinez, 2009). A comprehensive illustration of producing hydrogen through reforming fossil fuels in all three forms (i.e. gas, liquid and solid) is given in Figure 31. One example showing the process of generating hydrogen through coal gasification is illustrated in Figure 32. Since coal is mainly made up of methane, the production process using coal is accompanied by a large amount of carbon emission (see Figure 32), and is therefore not sustainable, even though it is noted that carbon emission through coal gasification can be reduced if carbon capture and storage technology is included into the process (Fayaz et al., 2012).

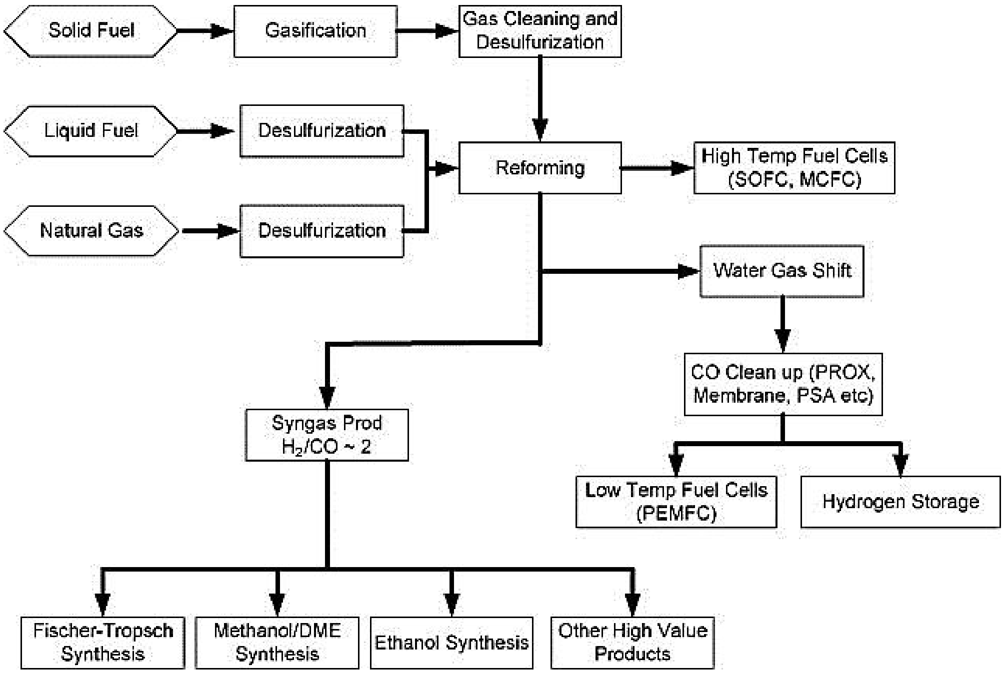

Figure 31: Hydrogen production through reforming of gaseous, liquid, and solid fuels (Holladay et al., 2009).

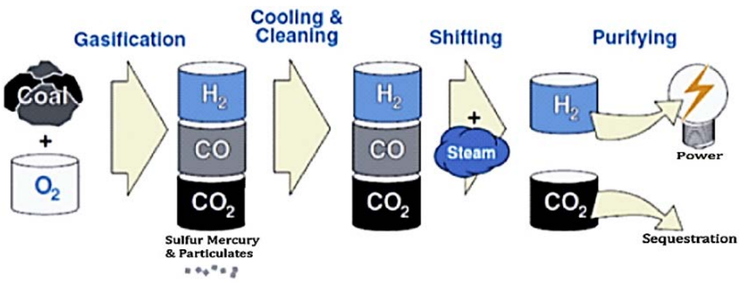

Figure 32: Coal gasification process (De Souza & Silveira, 2011).

Electrolysis is also utilised in industrial production of hydrogen. Different types of electrolysis include water electrolysis, high temperature electrolysis and proton-exchange-membrane (PEM) (De Souza & Silveira, 2011). Water electrolysis is the process of splitting the water molecule by passing electricity through two electrodes in water, and then to produce oxygen at the anode and hydrogen at the cathode. Said reaction can be demonstrated through the equation:

$$H_2O \rightarrow \frac{1}{2} O_2 + H_2 \quad 2.3$$

Electrolysis requires the input of electricity, which can be generated through either burning of fossil fuels or using renewable energy sources. Currently, the electricity input mainly comes from burning fossil fuels, however, water electrolysis using electricity generated from renewable energy is preferable due to its low environmental impact, with extremely low or zero carbon emission. This method has an efficiency of over 70% (Serrano et al., 2009). However, water electrolysis using renewable energy is more expensive with the present technology which hinders its commercialisation.

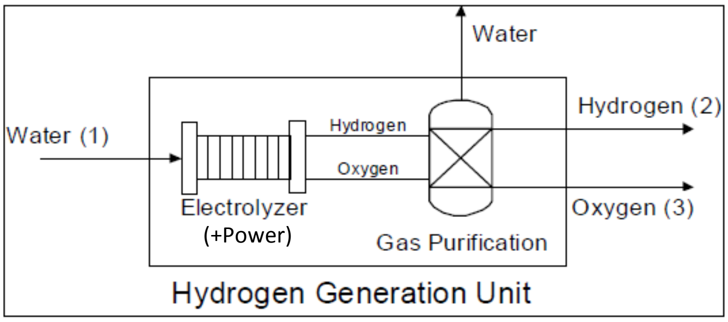

Figure 33: Sketch of hydrogen generator through electrolysis, adopted from (Laboratory, 2004).

Another method of generating hydrogen is through the photolytic processes (photosynthetic bacteria using solar energy), but this method is currently in early stages of research and is less frequently applied than the other ones discussed (Fayaz et al., 2012). Figure 34 shows an illustrative photolytic process of a photo-anode-based system using an n-type semiconductor. The process can be briefly summarised as the following steps (Holladay et al., 2009): (1) formation of an electron-hole pair resulting from a photon with greater energy than the band gap striking the anode; (2) water decomposition by the holes at the anode's front surface to form H^+ and O_2; (3) formation of H_2 through the reaction of H^+ and electrolyte at the cathode; (4) separation of H_2 and O_2, e.g. by the use of a semi-permeable membrane.

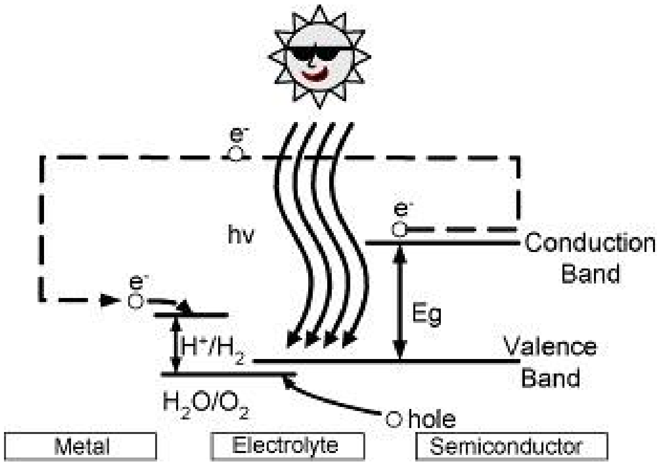

Figure 34: Energetic diagram of n-type semiconductor photo-electrochemical cells (Holladay et al., 2009).

2.2.2.2 Distribution (transmission and storage) of hydrogen

Once hydrogen is generated, energy from primary resources is then stored in it. This can then be distributed to the dispenser. Hydrogen can be stored either through physical or chemical storage. The former storage refers to the situation where hydrogen molecules are stored. An established physical hydrogen storage technology includes H_2 storage via compression and liquefaction. Chemical storage means the storage of hybrids. Therefore, in general hydrogen can be stored and distributed in three forms: gaseous, liquefied and solid (Fayaz et al., 2012; Pollet, Staffell, & Shang, 2012; Riis, Sandrock, Ulleberg, & Vie, 2005). The most promising methods for gaseous hydrogen technology under high pressure are composite tanks (as sketched in Figure 35) and glass micro spheres, but another option available is cryogas. Methods for liquid hydrogen storage include cryogenic liquid hydrogen (LH_2), $NaBH_4$ solutions, rechargeable organic liquids and anhydrous ammonia NH_3. Different options for solid hydrogen storage are given in Table 3 (Riis et al., 2005). A brief comparison between these different methods of hydrogen storage is summarised in Table 3 (Pollet et al., 2012; Riis et al., 2005).

Table 3: Overview of solid hydrogen storage options (Riis et al., 2005)

Carbon & other HSA* materials • Activated charcoals • Nanotubes • Graphite nanofibres • MOFs, Zeolites, etc. • Clathrate hydrates *HSA = high surface area	**Chemical hydrides (H_2O-reactive)** • Encapsulated NaH • LiH & MgH_2 slurries • CaH_2, $LiAlH_4$, etc.
Rechargeable hydrides • Alloys & intermetallics • Nanocrystalline • Complex	**Chemical hydrides (thermal)** • Ammonia borozane • Aluminium hydride

Table 4: Comparison between different options of hydrogen storage (Pollet et al., 2012; Riis et al., 2005)

Method	Pros	Cons	Status	Best options	R&D issues*
Gaseous hydrogen	Low weight; Well-engineered and safety tested; Accepted codes in several countries.	Low energy density; Energy loss in compression process.	Commercially available, but costly.	C-fibre composite vessels (6-10 wt% H_2 at 350-700 bar).	Fracture mechanics; Safety; Compression energy; Reduction of volume.
Liquefied hydrogen	High energy density;	Strict temperature requirement (-253 °C) → highly insulated liquid hydrogen tanks; Wast of 25% chemical energy of hydrogen in the liquefaction process.	Commercially available, but costly.	Cryogenic insulated dewars (ca. 20 wt% H_2 at 1 bar and -253 °C).	High liquefaction energy; Dormant boil off; Safety.
Solid hydrogen	Safe and efficient	(Taken metal hydride as an example): Very heavy; Time-consuming (long refuelling time); Insufficient release rate.	Very developmental (Many R&D questions).	Too early to determine. Many options including rechargeable hydrides, chemical hydrides (H_2O & thermally reactive), carbon, and other high surface area materials.	Weight; Lower desorption temperatures; Higher desorption kinetics; Recharge time and pressure; Heat management; Cost; Pyrophoricity; Cyclic life; Container compatibility; Optimization.

Hydrogen can be stored on-board or off-board. The former storage can also be regarded as transport of hydrogen where hydrogen is used as energy carrier for mobile applications. Off-board storage refers to stationary storage sites, including those central or distributed. Hydrogen can be stored on-board as liquid hydrogen, compressed hydrogen, metal hydride and hydrogen absorbed onto carbon nanotubes (CNT) and metal organic frameworks (MOF). Off-board hydrogen storage includes underground storage and pipeline storage. Underground storage uses underground caverns, salt domes and depleted oil and gas fields to store gaseous and liquefied hydrogen. Hydrogen can be stored in the existing pipelines used for storing nature gas, and an example of such study is given by NaturalHy ("Using the existing natural gas system for hydrogen," 2009).

Table 5: On-board hydrogen storage system performance targets (Satyapal, Read, Ordaz, & Petrovic, 2005).

Storage parameter	Units	2010	2015
Gravimetric energy capacity	kWh/kg (wt%)	2.0 (6.0)	3.0 (9.0)
Volumetric energy capacity	kWh/liter (gm H_2/liter)	1.5 (45)	2.7 (81)
Storage system cost	$/kWh ($/kg H_2 stored)	4 (133)	2 (66)
Cycle life (1/4 tank to full)	cycles	1000	1500
Minimum full-flow rate	(g/sec)/kW	0.02	0.02
Min/Max delivery temp from tank	°C	−30/85	−40/85
System fill time for 5-kg hydrogen system	min	3	2.5
Loss of usable H_2	(g/h)/kg H_2 stored	0.1	0.05

The ideal storage system should have optimum efficiency, while have weaker environmental impact and lower costs. Table 5 shows the target for on-board hydrogen storage according to the US National Renewable Energy Laboratory. It has been pointed out by Serrano et al. (Serrano et al., 2009) that the major problem with most existing hydrogen storage systems is their low efficiency, which causes a great waste of the energy produced. Different hydrogen systems are discussed and evaluated in a report given by Ahluwalia et al. (Ahluwalia, T. Q. Hua, J. K. Peng, & Kumar, 2010). That report lists the barriers of hydrogen storage, which include system weight and volume, system cost, efficiency, charging/discharging rates, thermal management, and system life-cycle assessment. In addition to research refining existing hydrogen storage technologies (compressed hydrogen and liquefaction of hydrogen), future research is focused on improving both chemical and physical storage technologies of hydrogen. For example, chemical storage technologies include metal hydrides, carbohydrates, synthesized hydrocarbons, liquid organic hydrogen carriers (LOHC), and carbonate substances; physical storage technologies include cryo-compressed hydrogen, carbon nanotubes, metal-organic frameworks, class capillary arrays, and class microspheres, to name but a few (Pedia, 2013).

Hydrogen supply between the producer and the dispenser also plays an important role in the whole hydrogen energy system. Hydrogen produced in a plant is either transmitted to a single point, or distributed to a network of refuelling stations or stationary power facility (Balat, 2008). Three main measures for transporting hydrogen are compressed gas pipelines, cryogenic liquid trucks and compressed tube trailers (e.g. see **Figure 35**). Comparison between these three pathways of hydrogen supply is given in Table 6. A list of four distribution methods in the sequence of decreasing environmental impact is: hydrogen gas by pipeline, hydrogen gas by cylinder, liquid hydrogen and hydride (Fayaz et al., 2012).

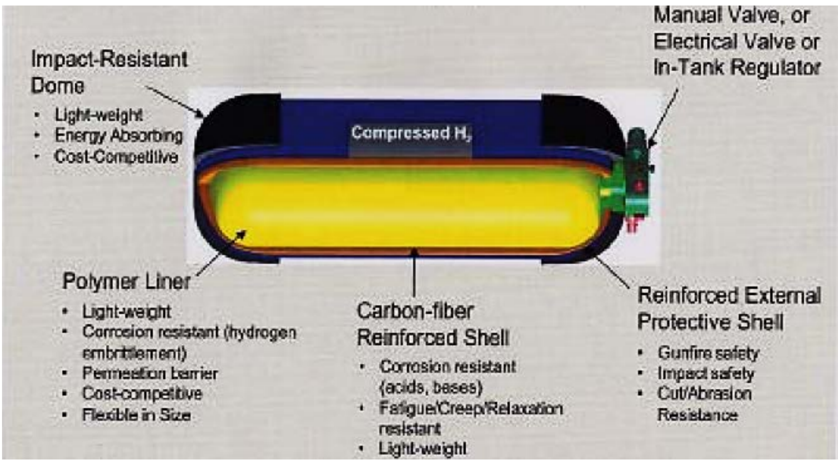

Figure 35: Schematic of a typical compressed H_2 gas composite tank (Riis et al., 2005).

2.2.2.3 End-use of hydrogen

Currently world hydrogen stands for approximately 2% of primary energy demand (Dupont, 2007). Hydrogen is being used in various applications which can be summarised as three main aspects: ammonia production, production of other chemical products and petrochemistry. Table 6 lists the share of hydrogen consumption in each aspect (Balat, 2008). As can be seen from Table 6, the primary hydrogen consumption goes to ammonia production (fertilizer making).

Table 6: Global hydrogen consumption in different aspects (Balat, 2008).

Hydrogen uses	Consumption (Bm^3)	Percentage
Ammonia production	250	50
Production of other chemical products	65	13
Petro-chemistry	185	37
Total	500	100

A relatively novel use of hydrogen different to those mentioned above is to replace fossil fuels as an energy provider for transportation or power generation. This has been seeing increasing attention worldwide, as a technical and political solution (Cherry, 2004). Hydrogen energy for transportation has the potential to reduce the carbon emission and is therefore considered environmentally friendly. In fact, the idea of using hydrogen as fuel is not so new and dates back to the early 19th century. The concept of the very first hydrogen car is illustrated in Figure 36 (Sequeira & Santos, 2010). Presently, hydrogen can be used as a fuel using either direct burning of hydrogen gas in an internal combustion engine (ICE) or fuel cells as basic propulsion. Both methods have higher efficiency than the gasoline counterparts: the efficiency of a hydrogen ICE is approximately 25 % and that of a hydrogen fuel cell is 60%, while the efficiency of a petrol ICE is around 18-20% (maximum 40%) (Pollet et al., 2012). The role of application of hydrogen in transport application is largely dependent on the relative gravimetric and volumetric energy densities of the various storage materials and systems (Andrews & Shabani, 2012).

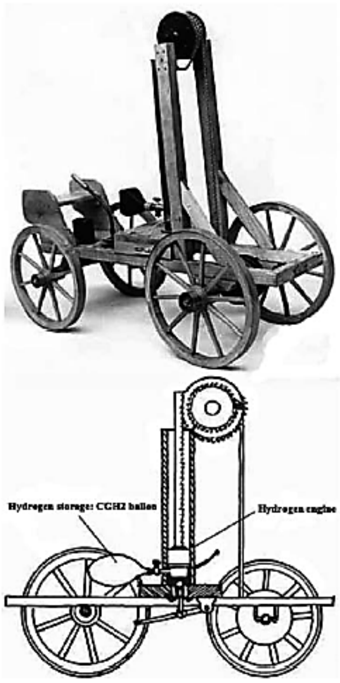

Figure 36: First hydrogen car invented by Francois Isaac de Rivaz in 1807 (Sequeira & Santos, 2010).

The major approach for using hydrogen in transport is to use hydrogen fuel cells for energy production. As hydrogen is an energy carrier rather than an energy source, the first problem that needs to be faced prior to its utilisation is energy conversion, i.e. accessing the energy stored in hydrogen. Fuel cells can be used to complete the conversion process and yield usable electric energy. When H_2 and O_2 are combined into water (H_2O) through a reverse electrolysis process in fuel cells, electricity is created. A schematic illustration of fuel cell is given in Figure 37. The work process of a fuel cell can be described briefly as the follows (Pritchard, Royle, & D, 2009):

- Hydrogen or a hydrogen-rich fuel is fed into the anode, where a catalyst separates hydrogen's negatively charged electrons from positively charged ions (protons).

- At the cathode, oxygen combines with electrons, and in some cases with species such as protons or water, resulting in water or hydroxide ions respectively

- For polymer electrolyte membrane and phosphoric acid fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons to generate water

- The electrons from the anode side of the cell cannot pass through the membrane to the positively charged cathode so they must travel around it via an electric circuit to reach the other side of the cell; this movement of electrons causes a flow of electric current.

There is a variety of fuel cells. Main of them include phosphoric acid, molten carbonate, solid oxide, direct methanol, alkaline and proton exchange membrane (Dunn, 2002). Operating principle of different types of fuel cells is given in Table 7 (Serrano et al., 2009).

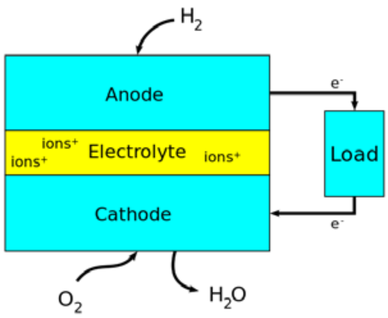

Figure 37: A block diagram of a fuel cell[14].

[14] Source: http://en.wikipedia.org/wiki/File:Fuel_Cell_Block_Diagram.svg

Table 7: Operating principle of different types of fuel cells (Serrano et al., 2009).

Fuel cell (FC) type	Anode reaction	Cathode reaction	Operating temperatures
Alkaline FC (AFC)	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$	**75 °C**
Polymer Electrolyte Membrane FC (PEMFC)	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	**80 °C**
Phosphoric Acid FC (PAFC)	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	**200 °C**
Molten Carbonate FC (MCFC)	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	**650 °C**
Solid Oxide FC (SOFC)	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$1/2O_2 + 2e^- \rightarrow O^{2-}$	**500–1000 °C**

The idea of fuel cells is not new. The first fuel cell was proposed in 1839 by Sir William Grove, who is known as Father of the Fuel Cell. However, it was only in 1950s when the first practical working models of fuel cells were developed by Frances Bacon. The fuel cell technology has only reached a commercial reality in the early 2000s. Nowadays, existing and emerging buses and ferries with hydrogen fuel cells are in service of public transportation all over the world. At the same time, the number of private cars using hydrogen fuel cells is also growing. Several commercially available fuel cells for transportation have been provided by a recent report of the U.S. Department of Energy (Inc. Breakthrough Technologies Institute, 2012), as shown in Table 8.

Table 8: Commercially Available Fuel Cells for Transportation 2011 (Inc. Breakthrough Technologies Institute, 2012).

Manufacturer	Product Name	Type	Output
Ballard	FCvelocity-HD6	PEM	75 and 150 kW
Hydrogenics	HyPM HD Modules	PEM	4, 8, 12, 16, 33 and 100 kW
Nuvera	Andromeda Fuel Cell Stack	PEM	100 kW
	HDL-82 Power Module	PEM	82 kW
UTC Power	PureMotion 120	PEM	120 kW

2.2.3 Risks and regulations

2.2.3.1 Risks regarding hydrogen

The properties of hydrogen relating to hazards and risks are mainly considered in the following aspects (Pritchard et al., 2009):

- Propensity to leak
  - Low viscosity
  - Extremely high diffusivity
  - High buoyancy
  - Small molecule/easy to escape from its containment
- Propensity to ignite
  - Wide flammable range in the air (4-75%)
  - Low minimum ignition energy (0.02mJ)/high ignition probability
  - Spontaneous ignition
- Propensity to leak
  - Rapid burning rate
  - Low rate of radiant heat
  - High tendency to detonation and deflagration
  - Odourless and colourless/difficult to detect with human senses

Hydrogen safety events may result in a wide impact on personnel, business and the environment. In terms of personnel impacts, hazards associated with hydrogen can be summarised in the following three categories (Rigas and Skelavounos, 2008):

- Physiological, including asphyxiation, thermal burns, frostbite, hypothermia, and overpressure injury
- Physical, including component failures due to low temperature deterioration of mechanical properties, thermal contraction, and hydrogen embrittlement.
- Chemical, such as burning or explosion

Hydrogen is neither much safer nor much more dangerous than the existing fossil fuels. A comparison of the risks and hazards between hydrogen, methane and gasoline is given in Table 9 (Rigas & Amyotte, 2013). Although it is found that gasoline "seems to be the easiest and perhaps the safest fuel to store because of its higher boiling point, lower volatility, and narrower flammability and detonation limits", it has also been pointed out that current technology is promising regarding the safety of using hydrogen.

Table 9: Pros and cons of hydrogen, methane and gasoline as fuels with regard to safety issues (Rigas & Amyotte, 2013).

Property or Event	Hydrogen	Methane	Gasoline
Size of molecules	Smallest molecule size resulting in highest leakage rate (+)	Small molecule size resulting in high leakage rate (++)	Big molecule size resulting in low leakage rate (+++)
Fire hazard from fuel spills	Fast development (+)	Intermediate development (++)	Low development (+++)
Fire duration	Shortest (+++)	Intermediate (++)	Longest (+)
Flame temperature	About the same	About the same	About the same
Odorization for leak detection	Not allowed if it is used as a fuel cell fuel (+)	Artificially odorized with mercaptans (++)	Normally odorous (+++)
Buoyancy	14.5 times lighter than air at NTP (+++)	1.8 times lighter than air at NTP (++)	Heavier than air (+)
Energy of explosion	Lowest per volume (+++)	Intermediate (++)	Highest per volume (+)
Flammability and detonability limits	Broadest limits (+)	Intermediate limits (++)	Narrowest limits (+++)
Ignition energy	One-fourteenth of methane and onetwelfth of gasoline (+)	Times 14 of hydrogen (yet static electricity discharges from a human body will easily ignite it) (++)	Times 12 of hydrogen (yet static electricity discharges from a human body will easily ignite it) (+++)
Autoignition temperature	Highest autoignition temperature (585 °C) (+++)	High autoignition temperature (540 °C) (++)	Low autoignition temperatures (227-477 °C) (+)
Deflagrations	Confined: Pressure rise ratio <8:1 (+) Unconfined: Usually <7 kPa	Confined: Pressure rise ratio <8:1 (+) Unconfined: Usually <7 kPa	Confined: Pressure rise ratio 70-80 % of hydrogen (++) Unconfined: Usually <7 kPa
Detonations	Pressure rise ratios of ~15:1 (+) Time to peak pressure: 10 times shorter than methane (+)	Pressure rise ratios of ~15:1 (+) Time to peak pressure: 10 times greater than hydrogen (+++)	Pressure rise ratios of ~12:1 (++) Time to peak pressure: 10 times greater than hydrogen (+++)
Shrapnel hazard	Ordinary enclosures (*L/D* < 30): About the same as for methane-air (+) Tunnels or pipes: Greatest risk due to tendency for DDT (+)	Ordinary enclosures (*L/D* < 30): About the same as for hydrogen-air (+) Tunnels or pipes: Lower risk due to tendency for DDT (++)	Somewhat less severe (++) Tunnels or pipes: Lowest risk due to tendency for DDT (+++)
Radiant heat	Lowest (lowest probability for domino effect) (+++)	Intermediate (++)	Highest (+)
Hazardous smoke	Least hazardous (+++)	Less hazardous (++)	Most hazardous (+)
Flame visibility	Lowest (+)	Intermediate (++)	Highest (+++)
Fire fighting	Most difficult (+)	Most difficult (+)	Less difficult (+++)
Total safety score	30+	33+	39+

2.2.3.2 Hydrogen safety

Handling hydrogen safely to ensure the viability and public acceptance of a complete energy system requires robust engineering design, training of the workforce and regulators the state-of-the-art knowledge in the field, and education of ordinary people. A profession of hydrogen safety engineering is emerging, which is defined as "*the application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen*". The emerging of the new profession indicates the increasingly important role played by the use of hydrogen as an energy provider, and hence the significance of associated safety knowledge.

For safe handling and mitigating risks to facilitate a smooth introduction of the hydrogen technology, an indispensable role is played by developing the appropriate codes and standards, as well as best practices made and continuously updated by increasing knowledge in hydrogen technology and lessons learned from incidents. Today, there exists a large information pool of standards and best practices for hydrogen safety, with experience mainly gained from history of using hydrogen in a wide variety of industrial settings, such as food processing. As the attention of the world on using hydrogen as a possible energy carrier grows, safety issues regarding hydrogen vehicles, refuelling stations and fuel cells are receiving an increasing interest and are being explored and researched in accordance of the need of a safety standards to follow. There are different safety practices from both global and regional perspectives. For example, globally, there is the international standards organisation (ISO) Technical Committee 197 "Hydrogen Technologies"; regionally, there are the UK regulations, the US regulations, the European regulations, etc. Many of the safety codes and standards are accessible online, for example from the website http://www.hysafe.info/?page_id=9 (from the organisation HySafe). Some existing regulations are listed in Table 10. It is noted that regulations about fire and explosion safety are also taken into consideration when drafting these standards.

Table 10: List of the selected regulations on both global and regional levels[15].

Region	Documents
ISO (international organization for standards)	**ISO TC 197**
UK	**Installation Guide for Hydrogen Fuel Cells and Associated Equipment;** **BS EN 50073 – Guide for selection, installation, use and maintenance of apparatus for the detection and measurement of combustible gases or oxygen**
US	**DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program Safety, Codes and Standards;** **Regulators' Guide to Permitting Hydrogen Technologies;** **US Hydrogen Industry Panel on Codes HIPOC;** **NFPA:** **NFPA 55 – Storage, Use and Handling of Compressed Gases and Cyogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks;** **NFPA 853 – Installation of Stationary Fuel Cell Power Plants**
EU	**First Regulation, Codes and Standards Workshop of the EU Hydrogen and Fuel Cell Technology Platform (HFP);** **EIGA public documents:** **IGC 75/01/E/rev – Determination of safety distances;** **ICG Doc 15/96 – Gaseous Hydrogen Stations**

Risk assessment regarding the use of hydrogen should be carried out in the overall energy system. A thematic structure in the overall hydrogen energy system is demonstrated in Figure 38. As can be seen, each vertical line indicates that every aspect regarding risks and hazards of hydrogen should be evaluated in all phases throughout the life cycle of using hydrogen as an energy carrier as specified in the transport sector. For every aspect regarding hydrogen hazards and risks, the whole system should be evaluated without ignoring any step in the life cycle of using hydrogen. At the same time, horizontally, each step of hydrogen energy system requires the evaluation of hazards and risks in terms of three aspects, namely, 1) hydrogen release, mixing and distribution; 2) thermal and pressure effects from fires and explosions; and 3) hydrogen mitigation technologies.

[15] Source: http://www.hysafe.info/?page_id=9.

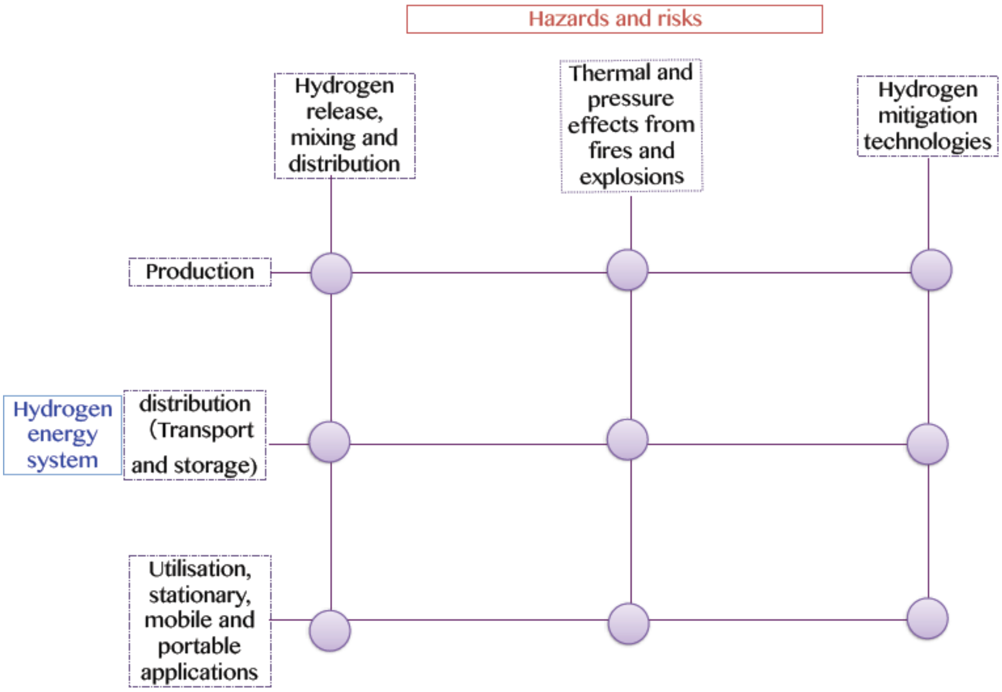

Figure 38: Thematic structure of hydrogen hazards and risks in the hydrogen energy system[16].

An important approach to enhance the existing safety measures and standards is to learn from the past incidents to prevent similar events from occurring in the future. There is never a limit to reach the top in this course. As clearly shown by the catastrophic Fukushima Daiichi hydrogen explosion in Japan in March 2011, our knowledge regarding similar incidents are far from sufficient (Rigas & Amyotte, 2012). Therefore, incident reporting is of vital importance. An *incident* can be defined as "*the loss of containment of material or energy*" (N. R. Mirza, Degenkolbe, & Witt, 2011). A summary of online resources for incidents reporting is given in Table 11 (N. R. Mirza et al., 2011).

[16] Adopted from Fig.1 of http://www.ineris.fr/centredoc/Engl_HySafe.pdf.

Table 11: Important databases about industrial incidents (N. R. Mirza et al., 2011).

Database Name	[a]Number of incidents	[b]Web address	Administered by
HIRD (Hydrogen Incident Reporting Database)	194	http://www.h2incidents.org/	Pacific Northwest National Laboratory, USA.
HIAD (Hydrogen Incident and Accident Database)	253	https://odin.jrc.ec.europa.eu/hiad/global_view.hiad	European Commission's Joint Research Center (JRC), Petten, Netherlands.
ACUsafe (US Chemical Safety Board monitored database)	No information available.	http://www.acusafe.com/Incidents/frame-incident.htm	US Chemical Safety Board, USA.
eMARS (Major Accident Reporting System)	743	http://mahb-srv.jrc.it/typo3/?id=4	Major Accident Hazards Bureau, JRC (EC), Italy.
FACTS (Failure Accidents Technical information System)	24,100	http://www.factsonline.nl/	TNO Industrial and External Safety Department, Netherlands.
ERNS (Emergency Response Notification System)	No information available.	http://www.rtknet.org/db/ems/substance	OMB Watch (A non-profit organization), USA.
ARIA (Analysis, Research and Information on Accidents)	37,000	http://www.aria.developpement-durable.gov.fr/barpi_stats.gnc	French Ministry of Ecology and Sustainable Development, France.
ARIP (Accident Release Information Program)	4946	http://www.epa.gov/oem/tools.htm#arip	Environmental Protection Agency, USA.

a last updated: 16th May, 2011.
b last accessed: 18th October, 2010.

The website Hydrogen Incident Reporting and Lessons Learned[17], launched in 2006 by the Pacific Northwest National Laboratory with funding from the U.S. Department of Energy, provides an assessable online resource platform to report incidents and share experience learned on an up-to-date basis (Weiner & Fassbender, 2012; Weiner, Fassbender, & Quick, 2011; Weiner, Kinzey, Dean, Davis, & Ruiz, 2007). Issues regarding the development, initial uses and subsequent enhancements of this website were first given at the Second International Conference on Hydrogen Safety (ICHS) (Weiner et al., 2007). Following that, in the Third ICHS, Hydrogen Safety Best Practices database (h2bestpractices.org) was described, the specific aim of which is to "*share the benefits of extensive experience by providing suggestions and recommendations pertaining to the safe handling and use of hydrogen*".

Analysis of the past incidents from the database of Hydrogen Incident Reporting can be valuable in terms of learning lessons to prevent similar incidents to happen in the future. Figure 39 shows the comparison of different settings of all incidents reported in the database by November 2011. It is seen that the majority

[17] Source: www.h2incidents.org.

of incidents occurred in laboratories. This situation continues in a more recent study (Rigas & Amyotte, 2013) which reported that laboratory accidents are the most frequent in all settings (accounting for 32.1%). In the study *Analysis of hydrogen incidents to support risk assessment* (N. R. Mirza et al., 2011), Mirza et al. analysed 32 incidents from the database regarding the causes, effects and consequences. The analysed causes of all the selected hydrogen incidents are given in Figure 40, from which it can be seen that most incidents were caused from technical insufficiency. These include all the causes resulting from wrong decision or installation of the wrong equipment by the on-site technical staff during operation. This indicates the importance of further knowledge and education of people handling hydrogen. Effects from these incidents are given in Figure 41, and it is found that fire is the primary effect, followed by explosion. However, combined fire and explosion is relatively rare. These hydrogen incidents in terms of different consequences are compared in Figure 42. Among all these 32 incidents, 87.5% of the incidents resulted in some adverse effect on the plant personnel or on the plant itself; while 12.5% of the incidents saw no significant damage, since these incidents resulted only in “leaks” or “near misses[18]” (N. R. Mirza et al., 2011). Only a small portion (4.6%) of all 32 incidents resulted in the loss of human life (Rigas & Amyotte, 2013).

[18] Near miss : An event, which under slightly different conditions might have become an incident.

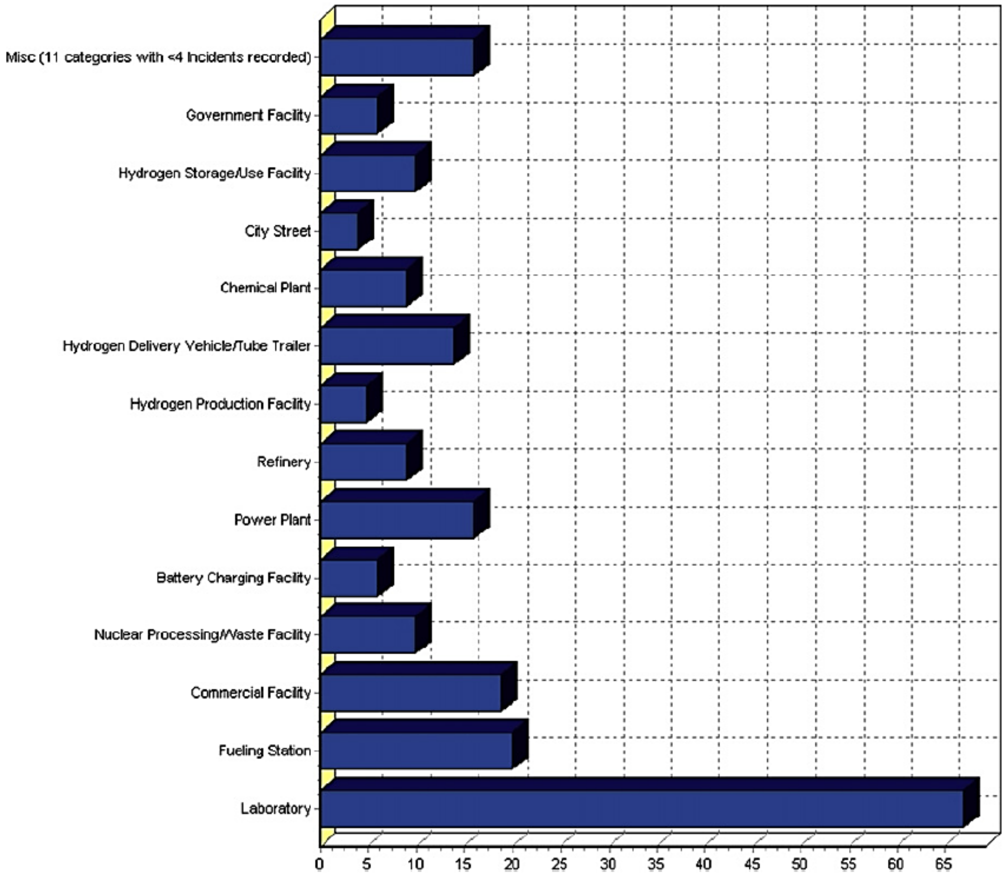

Figure 39: Bar graph showing settings of all incidents in the database (Weiner & Fassbender, 2012).

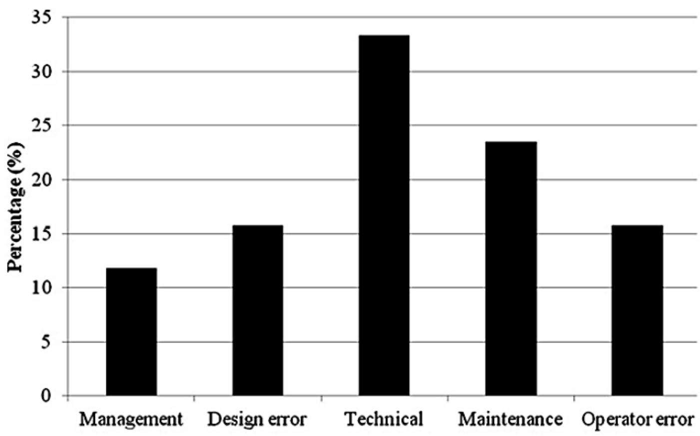

Figure 40: Analysed causes of H_2 incidents (N. R. Mirza et al., 2011).

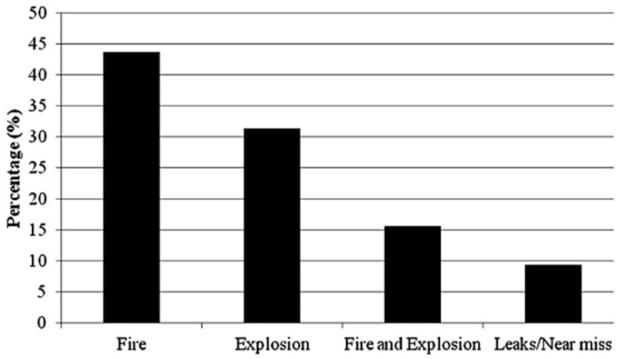

Figure 41: Effects of H_2 incidents (N. R. Mirza et al., 2011).

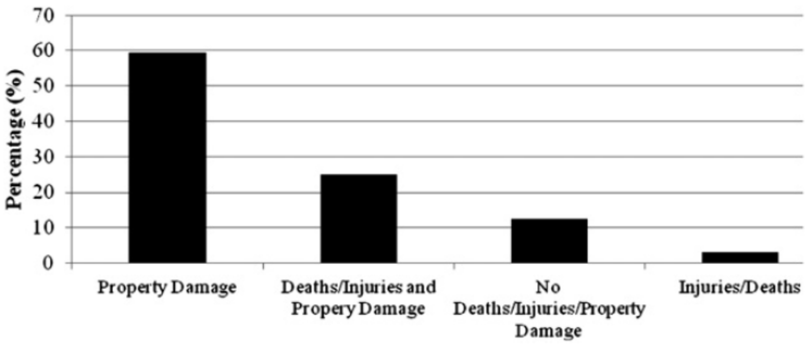

Figure 42: Effects of H_2 incidents (N. R. Mirza et al., 2011).

Regarding the reduction of the frequency of incidents and mitigating the harmful consequences of using hydrogen, there exist many other good models. For example, the network of a European project named HySafe mentioned before. All these organisations and practices have been contributing greatly to a more smooth transition to a hydrogen-based sustainable developing mode, or, a hydrogen economy (Winter & Nitsch, 1988).

2.2.4 The hydrogen economy

The concept of "hydrogen economy", first proposed during the oil crisis of the 1970s, typically refers to a developing mode which aims at the replacement of the vast consumption of petroleum fuels in transport applications with the use of hydrogen as an energy carrier. Since the latter is regarded as a viable and advantageous option for high-quality energy delivery for being efficient and environmentally friendly, the transition to hydrogen economy is considered as a promising way of dealing with rapid urbanisation and climate change to achieve sustainable development. As shown in Table 12 for the availability of modern transportation fuels, although gasoline is in an excellent availability currently, in the future it will be reduced to moderate or even poor availability; while on the contrary, the availability of hydrogen for fuel cells will improve from the present poor to excellent in the future (Balat & Balat, 2009).

Table 12: Availability of modern transportation fuels (Balat & Balat, 2009)

Fuel type	**Availability**	
	Current	*Future*
Gasoline	Excellent	Moderate–poor
Bio-ethanol	Moderate	Excellent
Biodiesel	Moderate	Excellent
Compressed natural gas (CNG)	Excellent	Moderate
Hydrogen for fuel cells	Poor	Excellent

The transition to a hydrogen-based economy system requires cautious and comprehensive considerations from the perspectives of politics, economy and environment. In terms of the transport sector, a summary of transportation greenhouse gas mitigation options and policies at present and in the future is listed in Table 13 (Balat & Balat, 2009). Policies and technologies are always updated with the concurrent availability and situation. A summary of the path of transition to hydrogen economy is shown in Figure 43.

Table 13: Summary of transportation greenhouse gas mitigation options and policies (Balat & Balat, 2009)

Category	Today's measures (deployable 2007–2015)	Tomorrow's measures (deployable 2010–2030)	Supporting policies and practices
Vehicle efficiency	-Incremental efficiency improvements in conventional gasoline automobiles and diesel trucks. -“On-road” improvements in maintenance practices, technology, driver education and awareness.	-Increased vehicle electrification (hybrid gas electric, plug-in hybrid, battery electric). -Fuel cell vehicles.	-Vehicle efficiency performance standards (fuel economy, CO_2 emission rate). -Voluntary industry commitments. -Vehicle purchasing incentives (rebates, feebates for low CO_2, high fuel economy). -Government and company fleet efficient vehicle purchasing.
Low greenhouse gas fuels	-Mixing of bio-fuels in petroleum fuels. -Use of lower GHG content fossil fuels (e.g. diesel, compressed natural gas).	-Electricity (in plug-in hybrids and battery electrics). -Cellulosic ethanol. -Hydrogen from renewable sources. -Mobile air conditioning (MAC) refrigerant replacement.	-Bio-fuel blending mandates. -Low GHG fuel standards. -Carbon tax on fuels. -Government and company fleet incorporation of alternative fuels.
Vehicle demand reduction	-Intelligent transportation system (ITS) technologies to improve system efficiencies. -Mobility management technologies. -Inclusion of GHG impacts in land use and transport planning. -Incentives and rules to reduce vehicle use.	-Greenhouse gas budgets for households and localities. -Modal shifts (road to rail freight, public transit systems). -ITS technologies to create more efficient transport modes.	-Road, parking, congestion pricing. -Investment in public transit. -Public awareness, outreach, education campaigns.

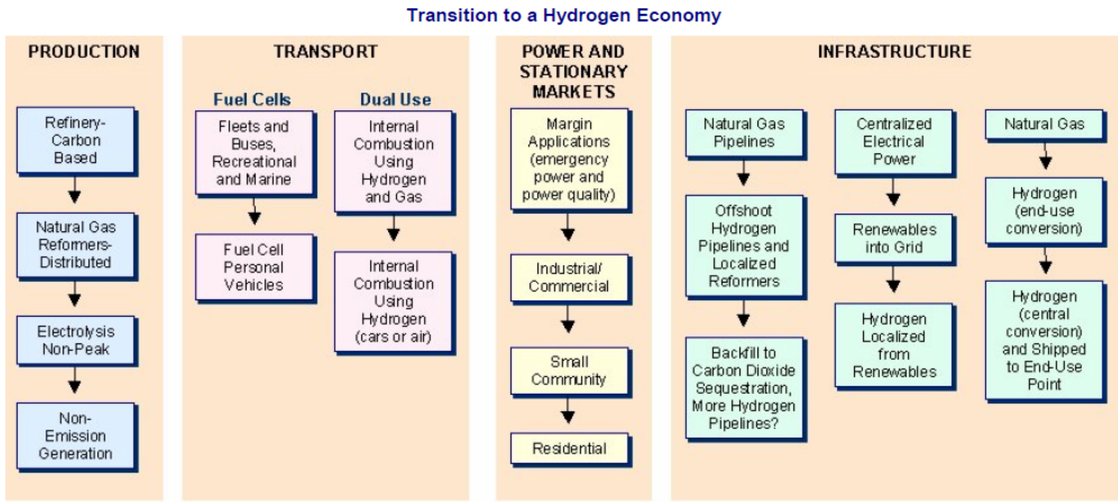

Figure 43: Transition to a hydrogen economy[19].

The hydrogen economy is a system which can be demonstrated in Figure 44. Basically, the system is consisted of two sections, i.e. the supply end and the demand end.

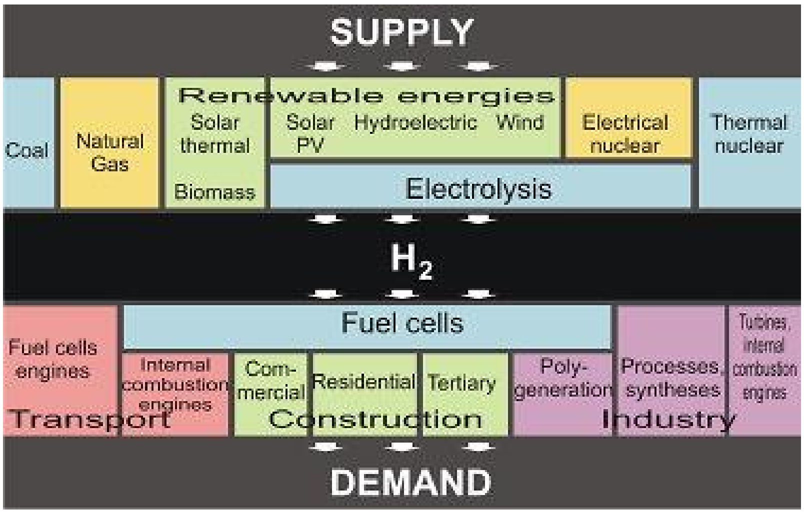

Figure 44: Summary of the hydrogen economy (Serrano et al., 2009).

2.2.4.1 Hydrogen supply

As mentioned in Section 2.2.2, at the present stage hydrogen production is mainly through the use of fossil fuels, which is currently the least expensive method. The share of hydrogen produced from fossil fuels is given in Figure 45,

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[19] Source : http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hv_report_12-17.pdf. Department of Energy, U.S.

from which it is seen that almost 1/2 amount of the hydrogen currently generated using fossil fuels is from natural gas, while only 4% is from electrolysis. It should be noted that hydrogen production from electrolysis with power generated using fossil fuels also gives off carbon emission, although the amount of such emission is noticeably smaller than producing hydrogen directive from steam reforming. In a word, hydrogen production from fossil fuels produces at least the same amount of CO_2 as the direct combustion of the fossil fuel, and is therefore not sustainable. The complete realisation of hydrogen economy requires completely zero carbon-emission, which means, the process for hydrogen production should also be zero emission. This is where the use of renewable energies (such as those types mentioned previously) for the generation of electricity fits in. The anticipated development of production technologies in the coming decades is shown in Figure 46.

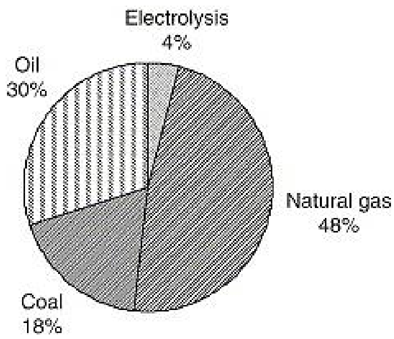

Figure 45: Coal gasification process (Kothari et al., 2008).

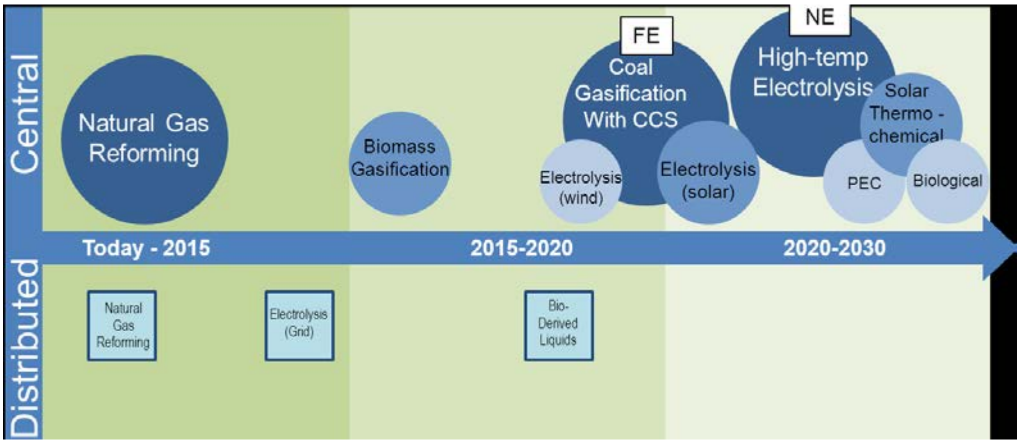

Figure 46: Generation of hydrogen in both central and distributed plants[20].

Hydrogen can be generated through electrolysis using the electricity generated from all types of renewable energies mentioned before. That is, the electrical power requirement for the renewable-energies-based electrolysis process can be provided by electricity generation through renewable energies, such as wind via wind turbines, or solar energy via PV panels, or other renewable energy methods (Ozbilen et al., 2013). It is noted that the CO_2 emission is not ideally zero, if taken into consideration the producing process of the facility and equipment of using renewable energies. For example, it is reported that in the process of wind/electrolysis, 78% of the corresponding global warming potential (GWP) is associated with wind turbine production and operation (Spath & Mann, 2004). However, since in general the CO_2 emission throughout the whole life cycle of hydrogen energy system is still largely reduced through using renewable energies, it is still the most promising solution for a sustainable developing mode due to its obvious advantage compared with using fossil fuels. The efficiency of hydrogen generation process using different renewable energy sources has been studied in various researches. Comparison of the resultant global warming potential GWP and acidification potential (AP) from using wind and solar energy is given in Table 14.

[20] Source: http://www.hydrogen.energy.gov/pdfs/review12/joint_plenary_satyapal_2012_o.pdf.

Table 14: GWP, AP and energy efficiency values per kg hydrogen production for hydrogen production methods (Ozbilen et al., 2013).

Hydrogen production method	GWP (kg CO_2-eq)	AP (g SO_2-eq)	Efficiency (%)
Wind based electrolysis	0.97	2.58	70
Solar based electrolysis	2.50	8.06	70

2.2.4.2 Application of hydrogen

The hydrogen generated can be used in different aspects. Replacing fossil fuel with hydrogen as the energy supply for fuel cells and other hydrogen technologies play a major role in a substantial transformation towards a sustainable energy system which meets energy needs in a cleaner, more efficient and cost-effective way (Barreto et al., 2003). Figure 47 shows that although the current share of hydrogen for energy is only 3%, in 2100 this share is expected to increase to 49% (Barreto et al., 2003). At present, using hydrogen technologies for energy supply in the transport sector is still more expensive and less popular than using energy from fossil fuels; however, with the price increasing and depletion of the fossil fuel resource, as well as the development of hydrogen technology, using hydrogen as an energy provider is becoming more promising and cost-effective. Figure 48 provides a pathway for reducing the lifecycle cost for fuel cell engine vehicles (FCEVs) given by the US Department of Energy. It is expected that with the cost reduction achieved through research and development (R&D) work in all elements including manufacturing, fuel cell and hydrogen application, by 2020 the total cost can be reduced by approximately 47%.

Figure 49 shows the trend of hydrogen use in terms of three sectors, i.e. transportation, residential/commercial and industrial sectors. A great increase of hydrogen use can be seen in transportation and residential/commercial sectors, both of which are anticipated to reach to approximately 50% in 2100 (Barreto et al., 2003). In the meantime, the share of other fuels, including traditional fossil fuels, will be decreasing. The comparison of the shares of fuel cells and other technologies is given in Figure 50 (Barreto et al., 2003), from which it is seen that the share of fuel cells is very likely to exceed the share of other technologies in around 2050, and will take up about 70% of the whole market. It is anticipated that hydrogen in fuel cell powered cars and light trucks could replace consumption of 18.3 million barrels of liquid and gaseous fossil fuels as the preferred fuel for transportation by the end of this century (Balat & Balat, 2009).

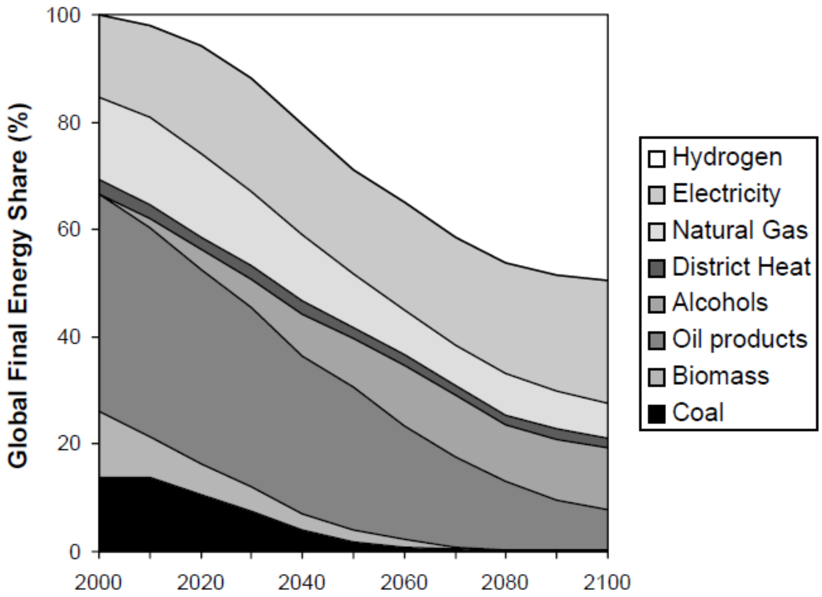

Figure 47: Evolution of global market shares of different final-energy carriers for the period 1990–2100 in the B1-H_2 scenario (Barreto et al., 2003). The alcohols category includes methanol and ethanol.

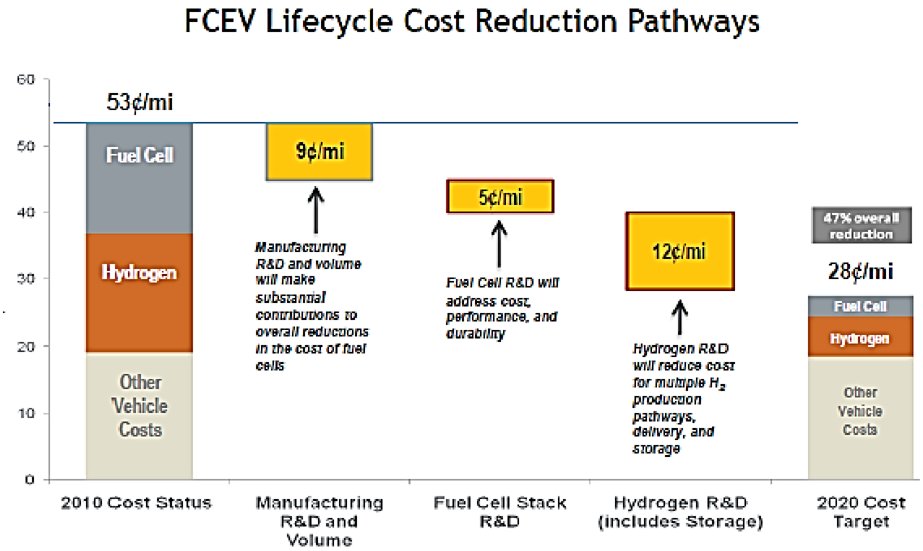

Figure 48: Cost reduction pathways for FCEVs[21].

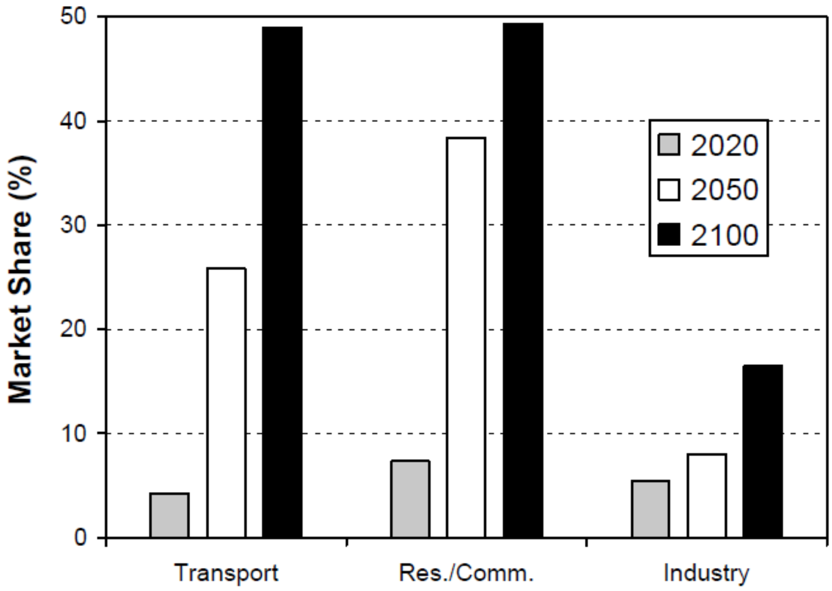

Figure 49: Global shares of hydrogen in transportation, residential/commercial and industrial sectors for the years 2020, 2050 and 2100 in the B1-H_2 scenario (Barreto et al., 2003).

[21] Source: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2011_market_report.pdf. Department of Energy, U.S.

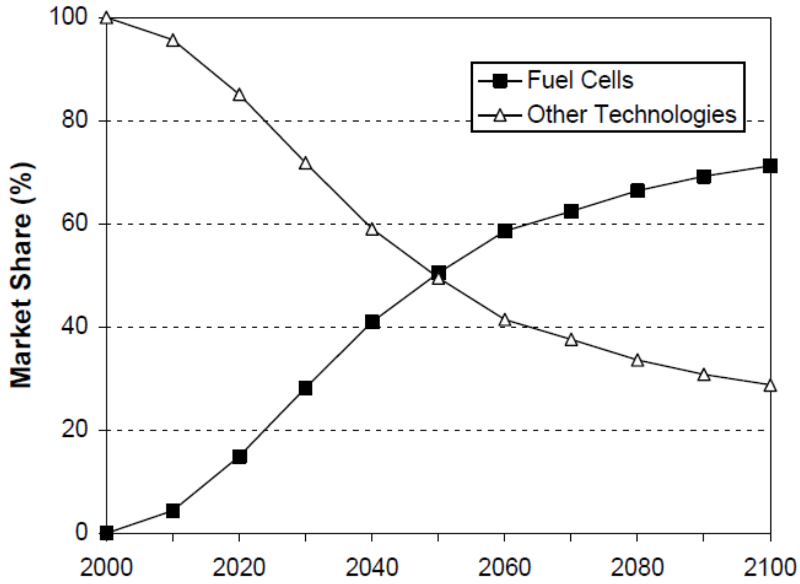

Figure 50: Evolution of the market share of fuel cells versus the aggregate of other technologies in the global transportation sector in the B1-H_2 scenario (Barreto et al., 2003).

3 Case study: Application of Hydrogen in public transport: City of Southampton

The core objective of this work is to analyse the possible future relevance of hydrogen from renewable energy sources (RES) for creating eco-friendly transport services in Southampton. The analysis addresses both economic and ecological aspects. Specific attention is paid to a comparison with the direct use of fossil and renewable energy sources to provide the same service.

3.1 The city of Southampton

3.1.1 Study Area

Southampton one of the largest located on the south coast of England (Figure 51) and is situated 75 miles (121 km) south-west of London and 19 miles (31 km) north-west of Portsmouth. Southampton is a major port of UK. It lies at the northernmost point of Southampton Water at the confluence of the River Test and River Itchen, with the River Hamble joining to the south of the urban area (Encyclopædia-Britannica, 2009). Southampton is the 5th largest growing city in UK. The city is also one of the UK's largest ports and the largest cruise-liner home ports (in terms of passengers handled) in Europe is the second largest UK container port.

Figure 51: Map of Southampton[22].

Following the definition of coastal areas in the Millennium Ecosystem Assessment (2003) Southampton can be considered as a coastal city (as a sheltered coast) that is located 100Km landward from the shore and within 50 m below mean sea level and 50 meters above the high tide level, includes estuaries, wetlands and intertidal zones.

3.1.2 Issues in the city of Southampton

The city has a steady growing population, population increased by 8.9% from 2001 to 2011. The present population of the city is 236,882 and largest growth (~ 12%) in the population is in the young or working age group (16-44 years). The rapid growth rates in the working age section of the population needs to be supported by creation of new jobs. Opening of new job opportunities in the city is a major issue for the city council. CO_2 emissions in the city are mostly from the use of fossil fuels and are directly related to the use in buildings, transport and industrial activities. The city's annual carbon footprint from transport is 247,000 tCO_2 (1.1 tCO_2 per person). The city is committed to meet UK government's target to reduce carbon emissions by 80% by 2050 (compared to 1990 levels) with an interim target to reduce CO_2 emissions by 34% by 2020.

[22] Source: Wikipedia.

Flooding is one of the most significant challenges for Southampton about 22.8% of properties are in flood zone, tidal (sea) and fluvial (from rivers) flooding along surface water flooding (due to precipitation) and overflowing sewer systems are the immediate concerns to the Southampton city council.

3.1.3 Eco-friendly transport in Southampton

The city of Southampton moves has already low carbon future plan, it has a strong political will to make the city prosperous, congestion, pollution and carbon free. The city aims to make travel and transport more sustainable in the city. This work presents an integrated zero carbon public transport option for the city of Southampton. The work proposes setting up a coastal hydrogen power plant that totally relies on energy from renewable sources. The hydrogen produced in the plant will be used in fuel-cell equipped vehicles to serve an integrated transport system of buses and ferries.

The British national transportations regulations have proposed to increase the use of water and improvement of the current road traffic to deal with congestion (ABP Southampton [23], 2011). Given the current state and the planned development of the city of Southampton, the Itchen River offers the potential to follows these suggestions.

To introduce a hydrogen passenger ferry to the city transport, there is a need to add additional bus links. Thus, the proposal is to use hydrogen buses in order to decrease carbon footprint. The main idea behind this is to create a unified complementary network consisting of city buses and river ferries.

After the consultation with the Southampton City Council, it appeared that the idea of hydrogen buses is not feasible at this time mainly due to financial reasons, taking into account the fact that Southampton City Council is already involved

[23] Reference: ABP Southampton. (2011, October 20). http://www.southamptonvts.co.uk/admin/content/files/Capital%20Projects/Appendix%20M%20-%20Transport%20Assessment.pdf.

in a process of incorporation of a different type of energy saving mechanism to the existing bus fleet. Therefore, for the engineering aspect, the project focused on development on Hydrogen Ferry operating on Itchen River. We proposed an integrated network of water and bus transport system which the city council may consider in near future.

3.2 Application of hydrogen energy - Marine

3.2.1 Introduction

Hydrogen Fuel cell technology has recently been proven successful in multiple maritime demonstration projects, those include: FCS Alsterwasser (Hamburg, Germany), Nemo H2 (Amsterdam, Netherlands), Hydrogenesis (Bristol, UK), Hydra (Germany).

Main reasons for developing maritime fuel cell technology are reduction in fossil fuel consumption and less local and global impacts of emissions to air from ships (DNV, 2012). Additional benefits include insignificant noise and vibration levels, and lower maintenance requirements compared with traditional combustion engines, mainly due to a lower number of moving parts.

There are some issues related to this technology that are currently being successfully addressed, such as decrease of the investment costs, improvement of the service lifetime, along with the reduction of the current size and weight of fuel cell installations (DNV, 2012) (Proton Motors, 2013).

3.2.2 Definition of a fuel cell

The first classification society rules governing the use of fuel cells were published by DNV in 2008 (DNV 2008) and class guidelines were issued by GL in 2003 (GL 2003; DNV 2012).

According to the Germanischer Lloyd Aktiengesellschaft, Hamburg, a **fuel cell** is defined as follows: a fuel cell is a source of electrical power in which the chemical energy of a fuel is converted directly into electrical energy by electrochemical oxidation (also known as "cold combustion", GL 2003).

Based on the same regulations the **fuel cell stack** (FC stack) is defined as a unit consisting of several fuel cells that are electrically connected in series, with internal interconnections for electricity and gas/liquid. An FC stack in the terms of these Guidelines also includes the pipe connection fittings as well as the connections required to supply the electrical energy (GL 2003).

Fuel cell system contains fuel cell stack and the complete balance of plant that supplies the stack with the essential media components (Proton Motor, 2011).

3.2.3 Overview of existing hydrogen craft

Table 15: Comparison of existing fuel cell ships projects based on the proton exchange membrane fuel cell technology (PEMFC) (McConnellx, 2010).

Key suppliers	Country	Type	Power rating	Date	Vessel name, notes
Non-nuclear submarines					
ThyssenKrupp Marine Systems/HDW	Germany	PEMFC	9 × 34 kW (in U31) 2× 120 kW (later subs)	2005	SiNavy PEMFC from Siemens, first contracted for class 212A sub in 1996, U31 and U32
UUV/AUV submersibles					
Perry Technologies/Ballard	USA/ Canada	PEMFC	3 kW	1989	PC-14
Atlas Elektronik/ZSW	Germany	PEMFC	160 kW	2002	DeepC, prototype with ZSW fuel cell
Mitsubishi Heavy Industries	Japan	PEMFC	4 kW	2004	Urashima, 317 km long-distance cruise record at 800 m depth, metal hydride storage
Yachts/sailboats					
IESE–EIVD	Switzerland	PEMFC	300 W	2002	Branec III used PEMFC as an auxiliary power unit (APU) in 6600 km transatlantic Route de Rhum race
MTU CFC Solutions/Ballard	Germany/ Canada	PEMFC	4.8 kW	2003	No. 1, 12 m yacht, CoolCell PEMFC in hybrid system with batteries as an auxiliary power unit (APU)
Voller Energy	UK	PEMFC	5 kW	2007	Emerald Beneteau 411, 12 m long, in 3000 nm ARC transatlantic rally, running on reformed LPG
Research vessels					
Icelandic New Energy/Ballard	Iceland/ Canada	PEMFC	10 kW	2009	Elding, 125-tonne whale watching ship with hybrid PEMFC/battery APU, part of Smart H2 Program
Water taxis/ferries					
Proton Motor	Germany	PEMFC	6–20 kW	2008	FCS Alsterwasser, 100 passengers, Zemships Project, primary propulsion with lead gel battery
Fuel Cell Boat BV	Netherlands	PEMFC	60–70 kW	2009	Nemo H2, 22 m long, 82 passenger capacity, hybrid with batteries for main propulsion
Recreational boats					
IESE–EIVD/ZeTek Power	Switzerland/ UK	PEMFC	3 kW	2003	Hydroxy 3000 catamaran, two earlier Hydroxy craft
University of Birmingham	UK	PEMFC	5 kW	2007	Ross Barlow waterway maintenance boat, student project
Horizon Fuel Cell/Plug Power	Singapore/ USA	PEMFC	300 W	2007	Trolling boat propelled by electric motors
Fronius International /Bitter GmbH	Austria	PEMFC	4 kW	2009	Riviera 600 motor boat (16 m long), H_2 in high-pressure cartridges, part of Future Project Hydrogen
Tropical Green Technologies	Greece	PEMFC	1 kW	2009	Testing RFC-1000 unit on motorboat, H_2 from reformed LPG
Rensselaer Polytechnic Institute	USA	PEMFC	4.4 kW	2009	New Clermont, 6.7 m Bristol 22 sailboat outfitted as student project with two Plug Power fuel cells

3.2.4 Current hydrogen-powered city ferries

3.2.4.1 FCS Alsterwasser

FCS Alsterwasser is a passenger ship entirely powered by hydrogen fuel cells developed by Alster-Touristik GmbH in 2008 to operate on Alster and River Elbe in Hamburg, Germany. It can hold up to 100 passengers. Operating with a cruising speed of 8 knots it needs to be refuelling every 2-3 days. The hydrogen fuel cells generate approximately 100 kW of electricity and have proven to be an extremely reliable energy source (Williams, 2012).

As quoted by(Henderson, 2011), this ship can save up to 1000 kg of NOx, 220 kg of SOx, 40 g of particulate and 70 tonnes of CO_2 thanks to the use of hydrogen propulsion over a conventional diesel power plant.

The vessel has received significant attention from the German Ministry of the Environment and Stuttgart Region Economic Development Corporation and has been awarded the f-cell award promoting the innovation, market potential and techno-economic viability of the project.

Figure 52: ZEMships FCS Alsterwasser.

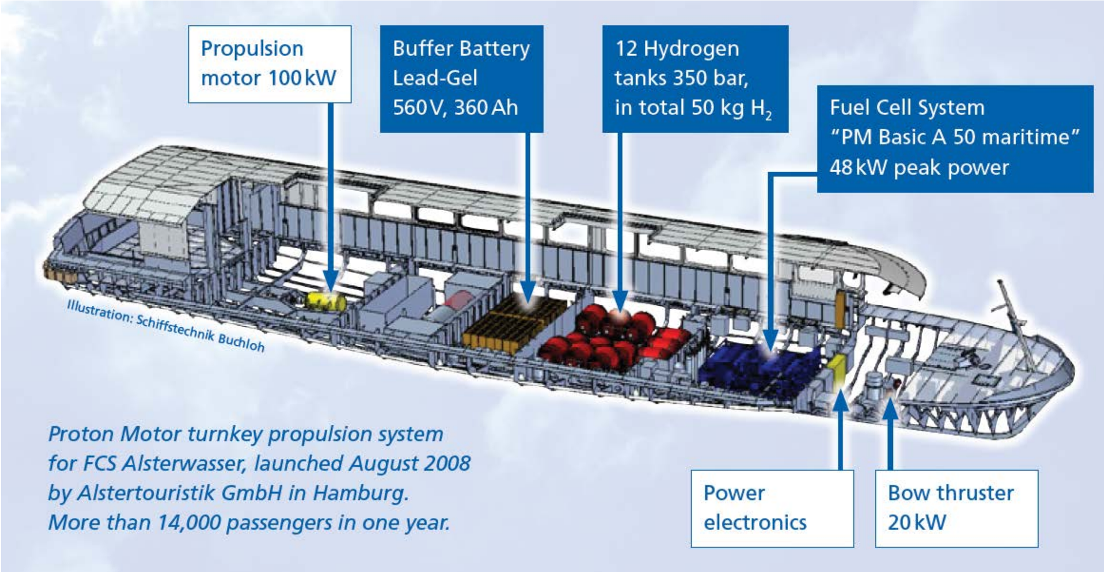

Figure 53: FCS Alsterwasser - general arrangement.

3.2.4.2 Nemo H2

Nemo H2 is a canal cruise boat that has been launched by the Fuel Cell Boat Construction B.V on 10th December, 2009 in Amsterdam, Netherlands. With a capacity of up to 88 passengers operating with a cruising speed of 9 knot her range is 9 hours (Henderson, 2010). The systems engineer of the vessel, Nico van der Hoeven from Alewijnse Marine Technology B.V. has been awarded with VNSI Timmers Award 2010 for young maritime designers as recognition of his work and display of technical skill on the development of the innovative automation system for Nemo H2[24].

[24] Souce: www.maritimejournal.com.

Figure 54: Fuel cell boat Nemo H2 (Lovers company) operates in Amsterdam since 2009[25].

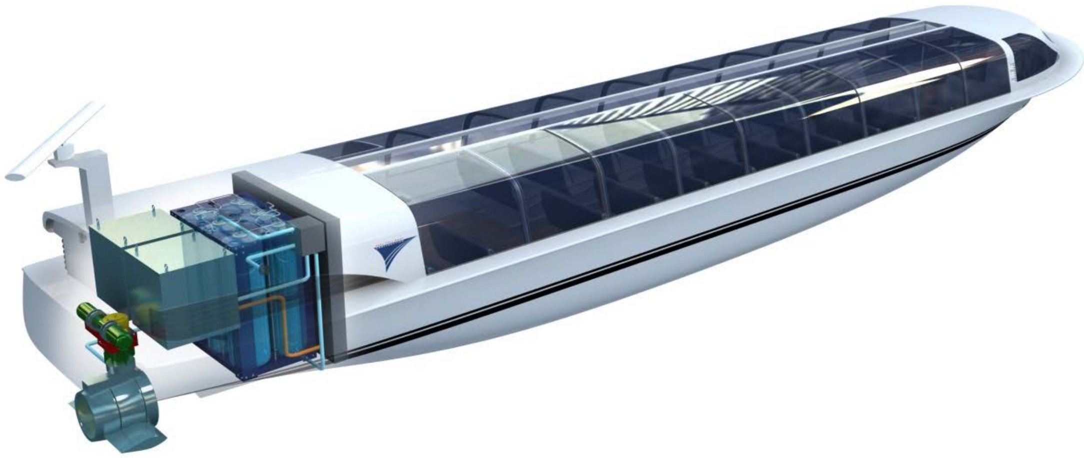

Figure 55: Nemo H2[23].

[25] Souce: www.vlootschouw.nl.

Table 16: Comparison of Nemo H2 and FCS Alsterwasser

Name	Nemo H2	FCS Alsterwasser
Draught	1 m, 65 cm above water level gangway	1.33 m (with passengers)
Air draught	65 cm	2.65 m (2.30 m using the roof lowering device)
Dimensions	21.95 m long and 4.25 m wide	25.46 m x 5.36 m
Tonnage displacement	45 tonnes	72 tonnes fully loaded
Capacity	87 +1 max 100	up to 100 passengers
Power	60-70 kW	2x48 kW
Propulsion	1 electrical stern thruster of 75 kW + 1 electrical bow thruster of 11 kW	propulsion motor 100kW + bow thruster 20 kW
Additional batteries	55 lead-acid batteries	7 lead-gel batteries (7x 80V)
Hydrogen storage:	24 kg stored in 6 cylinders at a pressure of 35 MPa	12 hydrogen-storage tanks 50 kg H2 at 350 bar
Type of fuel cell	Hybrid drive: 60-70 kW PEM fuel cell with 30-50kW battery	Proton Motor PM 600 Proton-Exchange-Membrane (PEM
Speed	16 km/h (8.6 kts)	15 km/h (8.1 kts)
Range	depending on boat speed but indicative 9 hours at a cruising speed of 7.5 kts	2-3 days
Material	steel	Steel and aluminium
Cost	The total project cost € 3 million. This can be divided into approximately € 1.8 million for the boat and € 1.2 million for the station. By SenterNovem is provided to grant for the overall project total € 1 million. The cost of the ship, after deduction of the grant will be paid by Company Lovers.	The total project cost € 5.8 million. This includes the boat and the station. The EU made a contribution of € 2.4 to the total ZEMSHIPS cost of € 5.8

3.2.5 Regulations/laws/legislations/guidelines

To safety introduce and operate a Hydrogen Fuel Cell powered passenger ferry on Itchen River multiple legal aspects need to be considered.

These mostly include the rules and regulations regarding fuel cells on board and refuelling infrastructure that need to be taken into account during whole life cycle of hydrogen powered craft operated on water managed by ABP (*Basic Safety and Operational requirements for future*, 2003):

- ISO 13984: Liquid hydrogen – Land vehicle fuelling system interface

- ISO 17776: Petroleum & Natural gas industries – Offshore production installations
- IGC code, PD5500, ASME VIII Div.1, AD Märkblätter
- DNV Rules for Classification Pt.4 Ch.7
- DNV Rules for Classification Pt. 6 Ch. 23
- IEC-105/40 Committee Draft, "Test Methods for Performance of Fuel Cell Power Systems", WG-04, IEC-62282-3-2
- LR Rules for the Manufacture, Testing and Certification of Materials
- ANSI-Z21.83.1998, "Fuel Cell Power Plants“
- GL VI - 3 Guideline for the use of FC systems on board of ships and boats

Below is given the list of bodies that need to be consulted within this project:

- ABP Southampton
- Maritime and Coastguard Agency
- Southampton City Council
- Crown Estate
- The Environment Agency
- Classification Societies

3.2.6 Proposed hydrogen ferry solution for Southampton

3.2.6.1 Route planning

In the route planning process multiple factors had to be taken into account, namely:

- New housing estates on a Woolston bank (Southampton Master plan)
- New housing estates to be built on the left bank of Itchen River (The Regeneration of Itchen Riverside, Southampton – Southampton Master Plan), see Figure 56
- Only one bridge (Itchen toll bridge) in this area
- Itchen River as an Environmental Protected Area - Southampton Port Master Plan (ABP Southampton, 2010)

- Southampton navigation charts (water depth and tidal tables)
- Currently existing potential infrastructure for the ferry stops and refuelling station (marinas, jetties and quays)
- Rules and regulations regarding operation on Itchen River (Maximum allowed speed – 6 knots) (ABP Southampton, 2010).

3.2.6.2 Economic aspects

The route has been planed to meet the demand of the local population to commute between the city centre and housing estates on both banks of Itchen River which now is limited due to the presense of only one bridge in this area. Potential usage of curently existing infrastructure (marinas) is suggested to both decrease the cost and to minimise the possible influence on the river ecosystem. The number of stops has been optimised to make comuting faster and economicaly afordable. Details of the final solution proposed are presented in Figure 57 and Table 17.

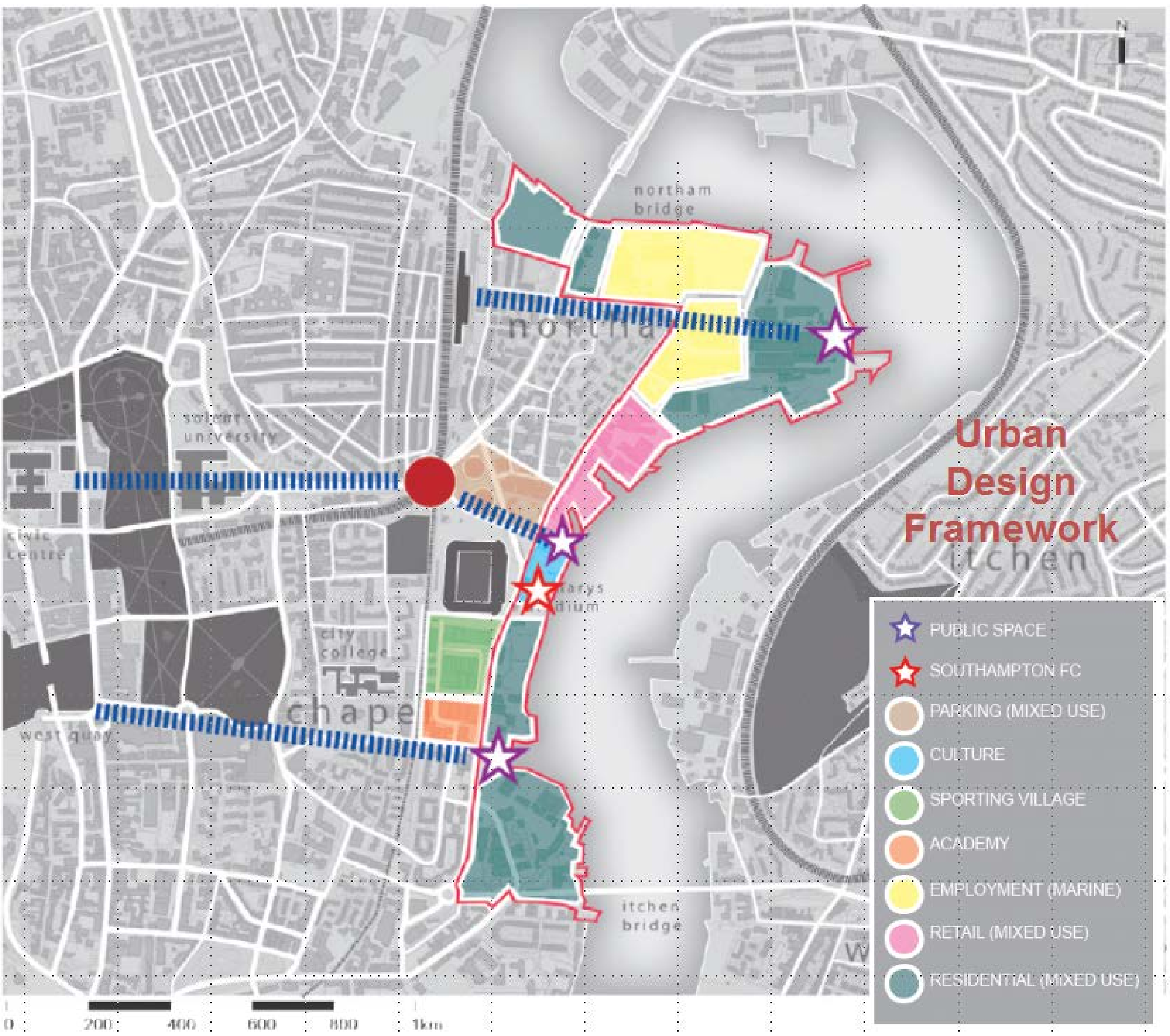

Figure 56: New Southampton City Council plan for regeneration of the left bank of the Itchen River (credits to Paul Nichols, Southampton City Council).

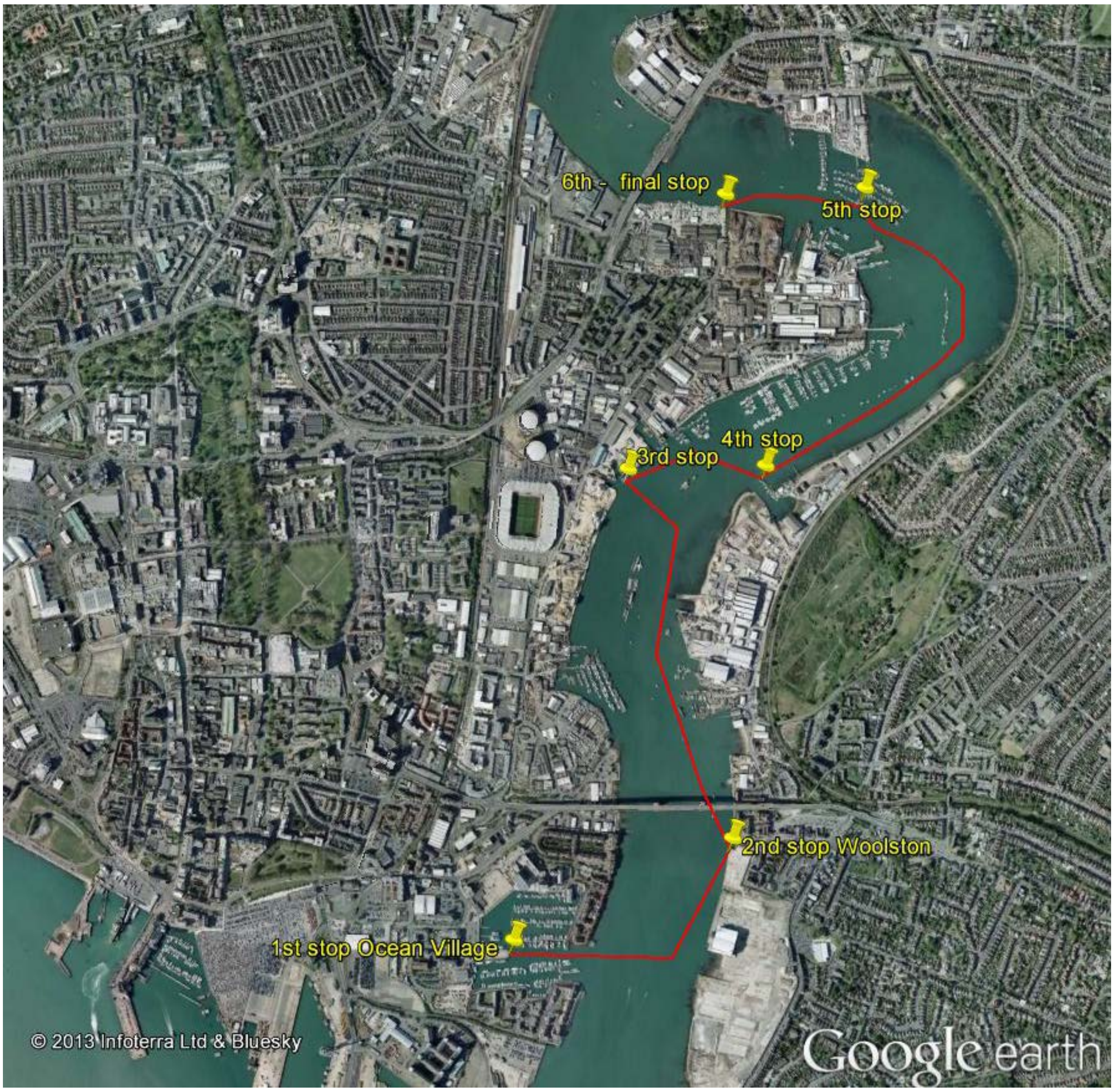

Figure 57: Proposed hydrogen ferry route connecting the city centre, current housing districts and the areas scheduled for revitalisation and development.

Table 17: Time and distance breakdown of the proposed ferry route.

Max speed [knots]	**6**
No. stops	6

Stop	Distance [nm]	Cumulated distance [nm]	Time [min]
1-2	0.41	0.41	4.1
2-3	0.59	1	10
3-4	0.16	1.16	11.6
4-5	0.21	1.37	13.7
5-6	0.85	2.22	22.2

3.2.6.3 Refuelling station

The exact location of a refuelling station has not been yet proposed due to necessary negotiations on possible usage of infrastructure that exist in the private marinas.

The principle functions of such a facility would comprise of storing hydrogen (most likely in liquid form at cryogenic temperatures), evaporating the gas, compressing it and loading it onto the ferry. To fulfil such purpose it would require specially insulated cryo-tank that allows storing LH_2 at -253ºC, appropriate system of pipes, pumps and compressors for handling the gas and a quay for mooring the vessel. To the authors' knowledge, it is a common misconception that hydrogen has to be stored far away from inhabited areas. As can be seen on example of Zemships & Linde hydrogen fuelling station in Hamburg Germany[26] this not necessarily has to be the case.

3.2.6.4 Ferry design considerations

The key concept in deciding upon the design of the ferry was to facilitate hydrogen propulsion as the primary source of energy for propulsion and hotel loads. This offers multiple advantages compared to the traditional diesel engine. Firstly, it produces no emissions during the vessel operation and hence allows the operation in protected and sensitive areas. Due to the lack of combustion and

[26] Source: www.fuelcelltoday.com.

moving parts, the level of noise and vibration is reduced to a minimum, which benefits the passengers, the crew, the marine wildlife and the inhabitants of the coastal areas. Coupling this technology with sufficiently large power storage ability allows the fuel to be used much more efficiently than in a standard diesel configuration, as the power plant can be operated at a more constant level with the batteries providing the additional output during the peak loads.

The ferry has been designed in a catamaran configuration due to its large available deck area combined with a low draught (0.775 m) and displacement, implying competitive power requirement characteristics. The principle design requirement was the capacity of 35 passengers, which has been estimated based on the prediction of possible number of users (similar to that offered by a standard city bus). Furthermore, it was required that the ferry should be able to carry disabled persons in wheelchairs, bikes and luggage. Additionally, fast loading and offloading of passengers had to be enabled, mainly due to facilitating wide gangways and doors. Due to safety considerations, it has been decided to place the hydrogen tanks on the deck, rather than inside the hulls, to provide easy means of inspection, refuelling and, in an event of a leak, mitigation of its consequences. Additional exits were placed either side of the passenger deck to provide emergency means of evacuation or a secondary way of embarkation of the passengers. The desired area of operation is subject to a maximum speed limit of 6 knots and so this had to be considered in the design process as well. As the ferry will be required to operate on a river cut by multiple bridges and so it was desirable to keep the air draught as low as possible. Through the adoption of a relatively small displacement, low draught and proportionally large demihull separation the wash of the vessel should be reduced to minimum, although a more in depth study would be required in order to analyse this more accurately.

After a review of the available off-the-shelf hydrogen power systems it has been decided to use a single system, given the relatively low power requirement of the vessel dictated by its low service speed. Additionally, a set of batteries has been accommodated to provide an additional power source to be called upon to support peak loads or in case of an emergency. Rudder propellers with permanent magnet motors were selected as the propulsion units as they offer superior manoeuvring characteristics, area readily available on the market and allow the two on-board power sources to be used freely at any power level. In order to ensure these can be fitted without increasing the draught and yet ensuring appropriate inflow into the propeller, the centre of buoyancy of the hull had to be shifted forward, which in turn governed where the batteries and fuel cell system should be placed.

Table 18: Design parameters.

Design parameter	Unit	Value
No. passengers	-	35
No. bicycles	-	5
No. wheelchairs	-	2
No. crew	-	1
Service speed	kts	5
Refuelling period	days	1
No trips / day	-	7
power reserve	% Fuel cell power	30

Table 19: Dimensions of a designed hydrogen ferry.

Dimensions		
LWL (length of the waterline)	m	11.355
bwl (waterline beam of the demihull)	m	0.845
bOA (beam overall of the demihull)	m	0.900
T (draught)	m	0.775
LOA (length overall)	m	11.700
S (separation of the demihull centrelines)	m	4.000
demihull clearance	m	3.155
BOA (beam overall)	m	4.900
Cb (block coefficient)	-	0.502
Cp (Prismatic coefficient)	-	0.636
Displacement demi	m^3	3.732
Displacement	m^3	7.498
Displacement	kg	7682.662
Deck area	m^2	57.33
WSA (wetted surface area)	m^2	33.6
D (depth of the hull)	m	1.8
Air draught	m	3.025

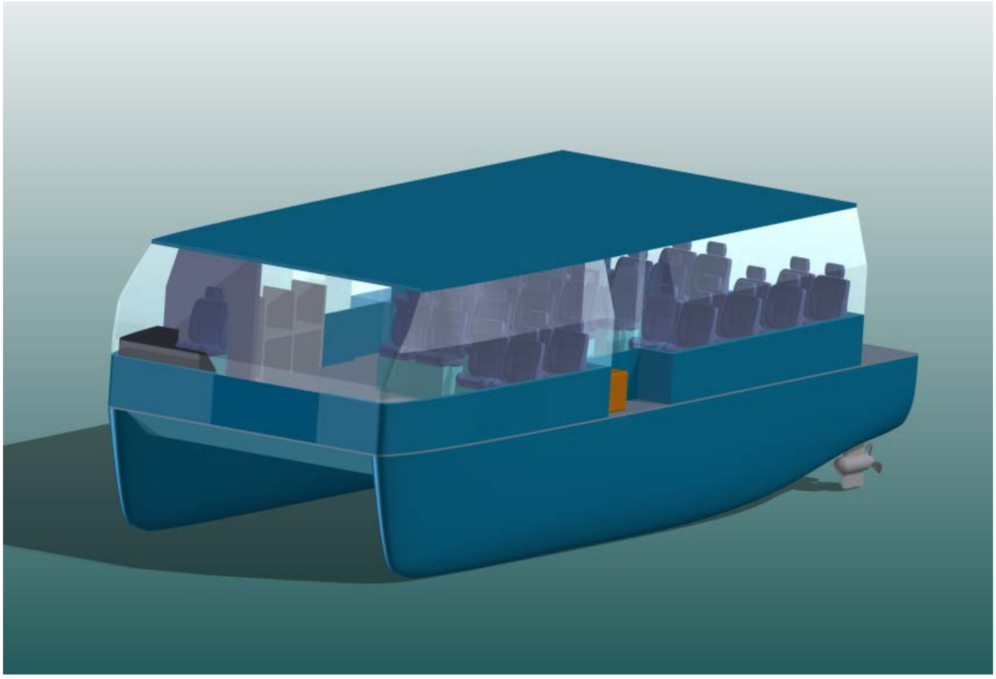

Figure 58: Hydrogen ferry designed for operation on Itchen River (Southampton).

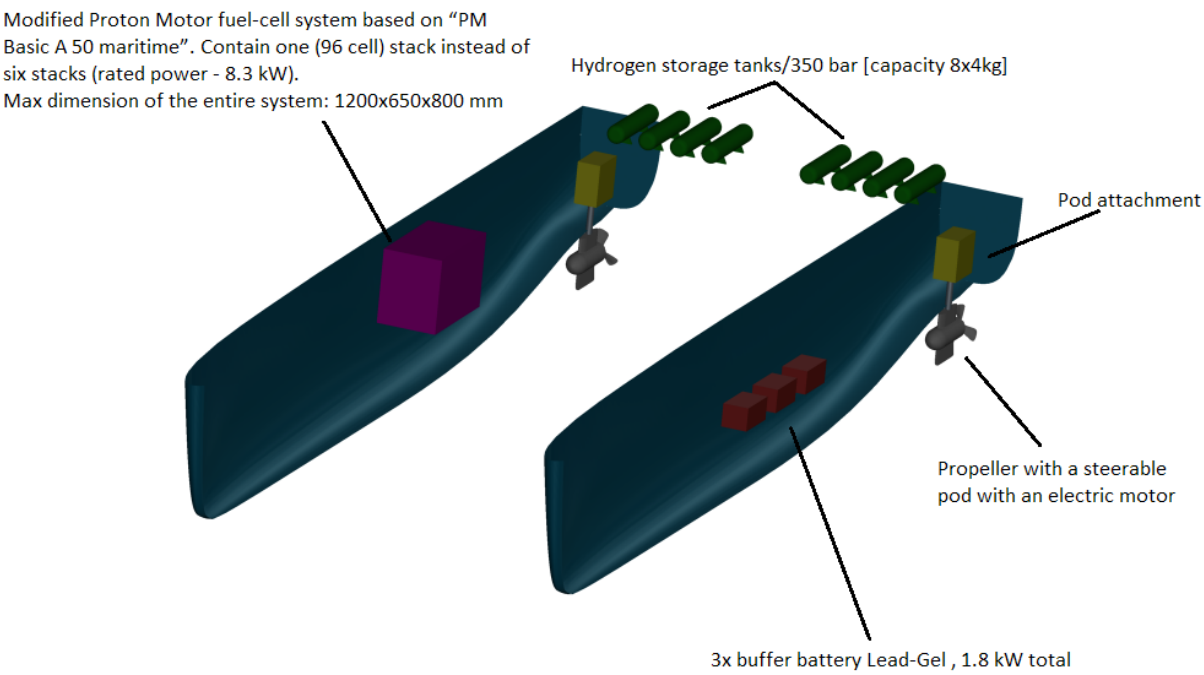

Figure 59: Technical data and general arrangement regarding the on-board installations.

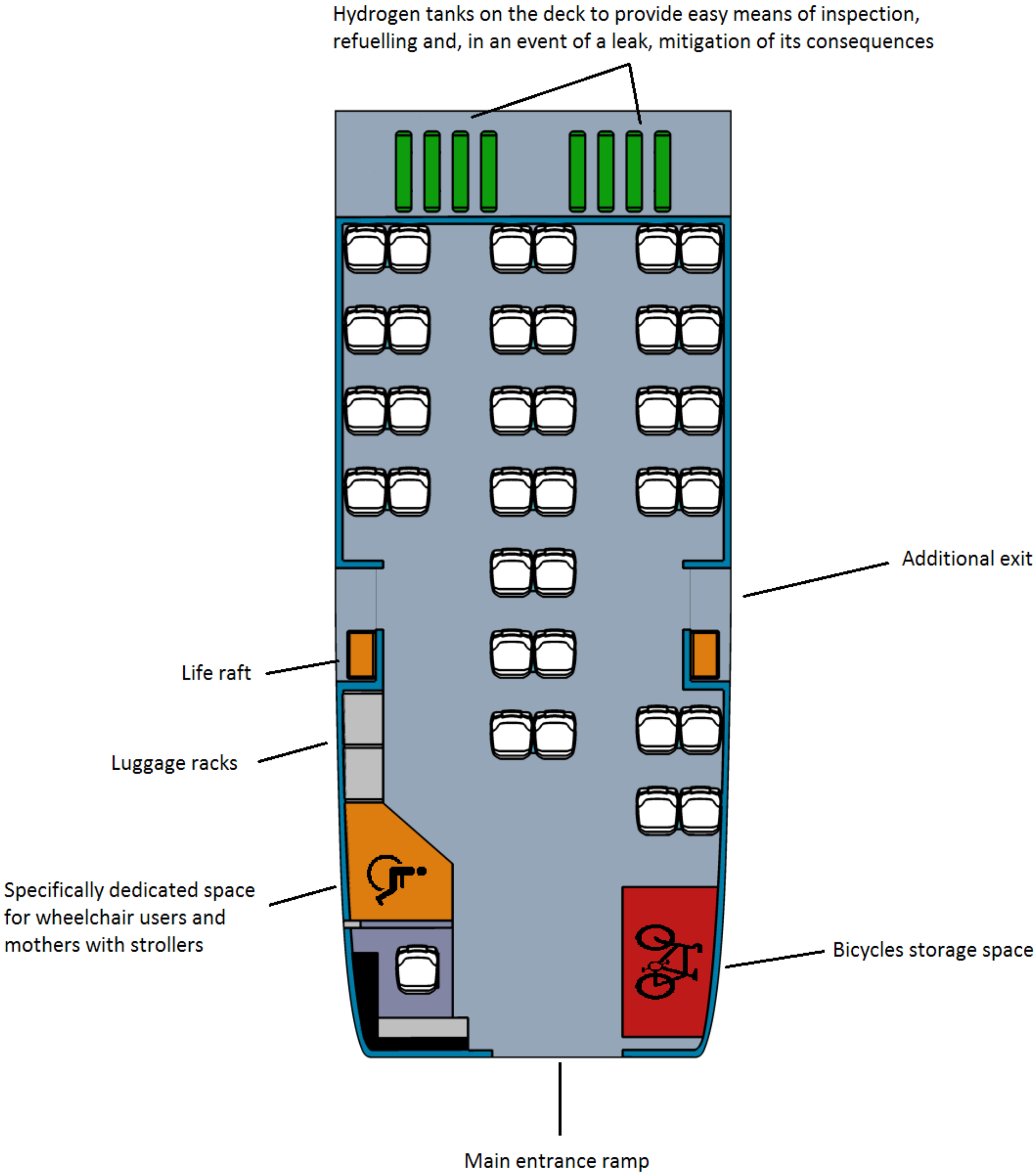

Figure 60: General interior arrangement plan.

3.2.6.5 Marine hydrogen propulsion

3.2.6.6 Fuel cell system

The Proton Motor fuel cell system has been chosen due to its of shelves availability, reliability (certified by GL) and flexibility in terms of modification. Its principle characteristics are summarised in Table 20 and Table 21.

The Proton Motors fuel cell system is equipped with hard wired safety circuit which triggers an emergency shut down for either the complete fuel cell system or only part of the system. This may happen in case of overheating, over pressure or less flow and prevents system from the damage and hydrogen from escaping to the surroundings areas (Proton Motor, 2011).

Figure 61: Fuel Cell Stack PM200 2.0 kW to 8.3 kW electrical power (Proton Motor, 2013).

Table 20: Technical data of Proton Motors 96cell stack (Proton Motor 2013).

Technical data for 96cell stack*	
Rated power	8.3 kW
Target lifetime	>5000 h
Length/width/height	402/245/135 mm
Weight	15 kg
Current	up to 150 A
Voltage range	55 – 100 V
Efficiency**	> 52%
Fuel	neat hydrogen
Fuel / Air pressure	up to 600 mbar
Pressure drop air	< 150 mbar
Coolant	DI-water or ethyl.glycole
Stack temp.	up to 65°C***
Ambient temp. range	-20 – 60°C
Min. startup temp.	> 0°C
(* Further configurations available on demand, ** at rated power, * No need for external humidification)**	

Figure 62: A fuel cell system PM Basic A 50 maritime (Proton Motor 2013).

Table 21: Manufacturer description of the PM Basic A 50 maritime (Proton Motor 2013).

Fuel cell system PM Basic A 50 maritime
48 kW power
Optimised for maritime use
Certified by Germanischer Lloyd "FC100"
Compact design for integration under deck
Optimal for ships with 40 – 300 kW power requirement

3.2.6.7 Hydrogen storage

Hydrogen is stored on-board in his gaseous form under pressure of 350 bars.

Based on the comparative analysis of the performance factor (pressure x volume/mass) of various tank types presented by Isabelle Moysan (Military Applications Division CEA Valduc Center (Isabelle Moysan CEA, 2004-2005), as shown in Figure 63, plastic/carbon containers have been identified as most suitable for on-board hydrogen storage. It is also important to mention that this type of container is lighter, less expensive and exhibits longer life spans in comparison to aluminium lined tanks (Isabelle Moysan CEA, 2004-2005).

The capacity of single storage container is 4kg.

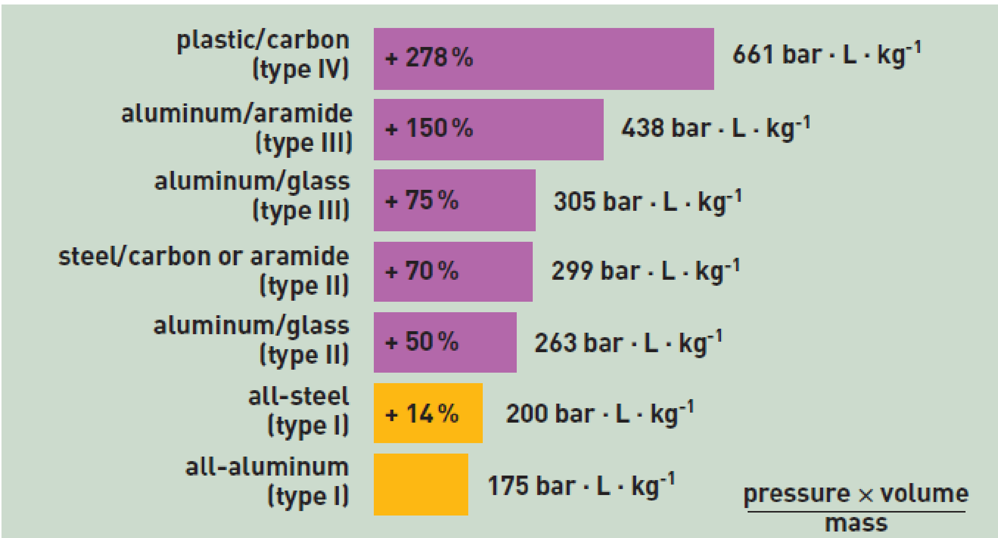

Figure 63: Comparative analysis of the performance factor (pressure· volume/mass) of various tank types (Isabelle Moysan CEA, 2004-2005).

3.2.6.8 Cost

The total project cost for the Alsterwasser is € 5.8 million. This includes the boat and the station.

The total project cost for the Nemo H2 is € 3 million. This can be divided into approximately €1.8 million for the boat and € 1.2 million for the station.

Due to the novelty of this technology it is hard to calculate the exact cost for the city of Southampton due to the lack of published data but based on the technical data of the designed ferry the cost is expected not to exceed £ 2.6 million (€ 3 million).

3.2.6.9 Future work

To successfully introduce the hydrogen ferry on Itchen River following steps need to be undertaken:

- Southampton City Council to cooperate with private owners of marinas to establish ferry stops and refuelling station infrastructure
- Cooperation between British Port Association and Southampton City Council to allow the ferry to operate on Itchen River
- Cooperation between Environmental Agency and Southampton City Council to monitor the environmental protected area
- Further development of the ferry design supported with a more in-depth techno-economic accounting for the progress made in the aforementioned aspects of the project

3.3 An integrated network of water and bus transport system

The goal is to cover one of the Uni-link service routes “U1” and integrate a new bus route (Figure 64), hereby named after “HydroLink” ring service with the ferry service route (Figure 57), for this 10 ferries are proposed servicing the River Itchen for a faster transportation.

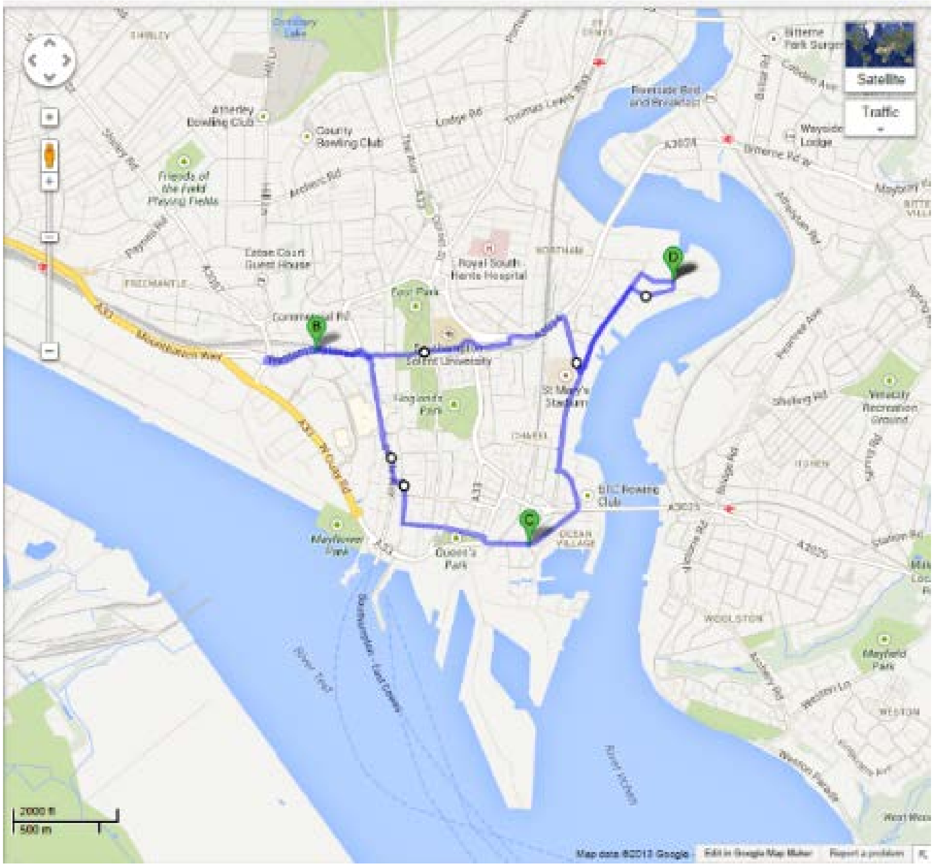

Figure 64: HydroLink route.

3.3.1 The HydroLink

HydroLink is envisioned keeping in mind the daily needs of future dwellers of the housing estates (according to Southampton City master plan) on both sides of river Itchen. The motivation behind this new route that links “city centre” with the Itchen riverside came after by answering the following fundamental questions; “What people would need to do?” or “where they would like to go”.

- For instance dwellers would want to go and watch football matches; therefore, St Mary’s (Saints’) stadium is covered twice.

- Dwellers would like direct connections to Central Railway station via Civic Centre.
- The route will also act as a key route for university students to attend the Southampton Solent University.
- The route also covers East Park and Palmerston Park and the historical Southampton sections for those who want to enjoy the city life.
- For those who want to sail with cruise ships, they can easily connect to the docks and international Southampton Port Via Queen's Terrace.

3.3.2 Ticketing

The unique aspect of HydroLink is that it introduces smart ticketing, by buying one single ticket (valid for one day) for HydroLink people can travel both sides of River Itchen and reach all the above mentioned destinations.

3.4 Evaluation of renewable energy potential for hydrogen production

Before implementation of such coastal hydrogen plant that would serve as energy source for the buses and the ferry services the potential and exploitable energy of the renewable energy sectors (wind, wave, tidal and solar) is evaluated. This section describes the survey and evaluation approaches applied in this work.

3.5 Evaluation of renewable energy potential for hydrogen production

Before implementation of such coastal hydrogen plant that would serve as energy source for the buses and the ferry services the potential and exploitable energy of the renewable energy sectors (wind, wave, tidal and solar) is evaluated. This section describes the survey and evaluation approaches applied in this work.

3.5.1 Approach

For the estimation of available renewable energy, a top down approach (Figure 65) is used (Biberacher, Gadocha, & Zocher, 2008; Hoogwijk, 2004). Based on the idea of Rodriguez et al.(Rodríguez et al., 2010) and modification of ours, four aspects is considered to assert the potential for the production of hydrogen from renewable resources:

- Evaluation of the renewable resources
- Annual requirement of hydrogen production
- Annual energy requirement for hydrogen production
- Analysis of the hydrogen production cost via suggested hydrogen plant

And one addition for this four aspects with respect to the work of Ajanovic (Ajanovic, 2008); energy service cost also should be considered.

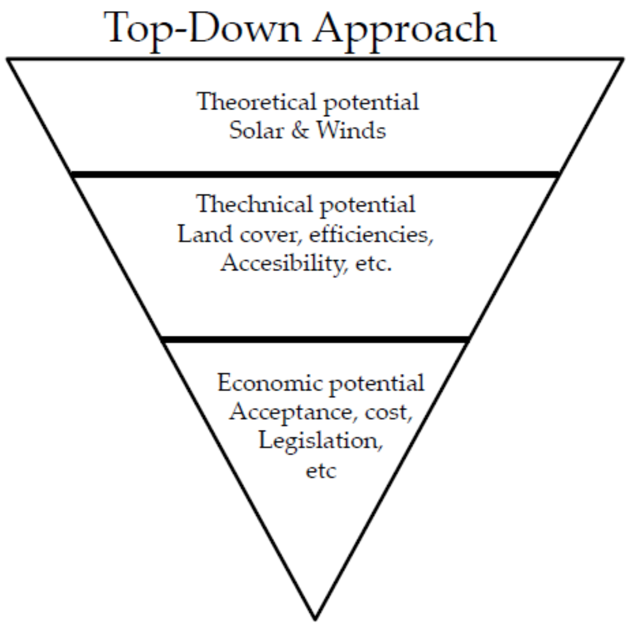

Figure 65: Top-down approach to estimate renewable energy potentials (adapted from Angelis-Dimakis et al. (2011) and reference there in).

3.5.2 Evaluation of renewable energy sources

3.5.2.1 Solar irradiation and wind data

Monthly averaged solar radiation (kJ/m^2) data from the period of 7/2000 to 7/2013; is used to calculate the average monthly and annual solar potential for the region (figure1). Wind speed (m/s) data obtained from MetOffice-UK and average wind speed data is used to study the monthly variations of wind (Figure1) and also evaluate the wind energy potential.

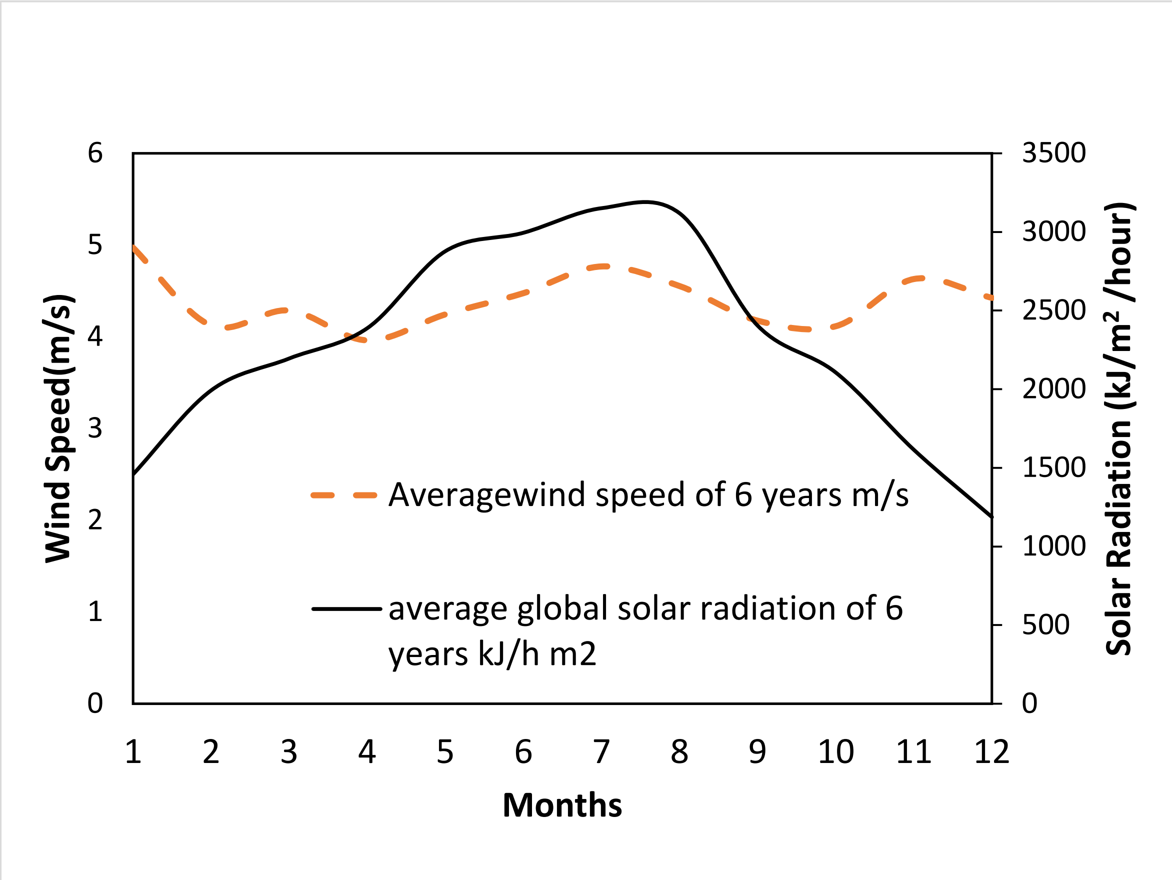

Figure 66: Monthly averaged solar radiation and wind speed data.

3.5.2.2 Calculation of theoretical potential

The energy produced by the photovoltaic (PV) system (kWh) can be easily calculated from the basic formulae following (Zejli et.al, 2011).

$$P_{pv} = A_{pv} * \eta_{pv} * \eta_{pc} * P_f * G \qquad 3.1$$

Where G is the perpendicular irradiance at array's surface [W/m^2] received by the PV module,A_{pv} is the PV area, η_{pv} is the module reference efficiency, p_f the packing factor and η_{pc} is the power conditioning efficiency.

The energy produced by the PV module [kWh] during the time period T can be expressed as equation 3.2

$$\boldsymbol{E_{pv} = \frac{\Delta T}{1000} P_{pv}} \quad 3.2$$

Equations 1 and 2 is combined to form equation 3.

$$\boldsymbol{E_{PV} = E_{data}\ x\ A_{PV}} \quad 3.3$$

where E_{pv} is the theoretical photovoltaic potential, E_{data} is the energy from the data (in kJ), A_{pv} is the PV module area (m^2). For the theoretical calculations 100% efficiency and a packing factor of 1 is assumed and solar panel area of 2x2 m^2 is considered. Under such assumption a maximum of ~ 800 kWh (2873944 kJ) energy and a minimum of ~ 82 kWh (293064 kJ) energy can be generated.

For wind turbines calculations are based on the theoretical kinetic energy of wind which can be given as

$$\boldsymbol{P_{wt} = \frac{1}{2000} \rho . A_s . V^3} \quad 3.4$$

ρ is the density of air (1.204 kg m^{-3}), A_s is the swept area of the blades of the wind turbine. Assuming a 7m diameter wind turbine with an annual average of wind speed of 4m/s theoretical potential is calculated to be ~1.5kW of energy.

$$\boldsymbol{E_{WT} = P_{WT}\ x\ \Delta t} \quad 3.5$$

where E_{pv} is the theoretical wind turbine potential and Δt is the time in hours, assuming that the areas receives steady winds of 4m/s for 6 hours daily, then one wind turbine in one month can theoretically produce approximately 972000kJ = 972 MJ of energy.

Since the goal is to assess the available H_2 potential, 1st law of thermodynamics is followed which states that *"energy can be neither created nor destroyed during a process it can only change forms"* (Çengel & Boles, 2006) to calculate the theoretical potential of H_2 from the solar data. The amount of H_2 mass that can be theoretically produced from both wind and solar energy can be expresses as

$$M_{H_2} = \frac{E_{H_2}}{LHVH_2} = \frac{\eta_1 . \eta_2 . E_{RE}}{LHV_{H_2}} \qquad 3.6$$

where M_{H2} (kg) is the hydrogen that can be theoretically produced, E_{H2} (kWh or kJ) is the hydrogen energy produced, LHV_{H2} is the lower heating value of hydrogen (kWh/kg or MJ/kg) which is 119.95 MJ/kg (Moran, Shapiro, Boettner, & Bailey, 2010). For the theoretical calculations electrolysis system is considered to be 100% efficient, η_1 and η_2 are the efficiency of the electrolysis system and the energy loss coefficients. E_{H2} produced from solar PV (E_{H2PV}) and wind turbines (EH_{2WT}) can then be calculated using equation (5).

$$M_{H2PV} = E_{H2PV}/LHV_{H2} \qquad 3.7$$

As it can be seen in the figure above, maximum energy production of PV is on July and the minimum is on December. Hence, the potential to produce hydrogen is:

Maximum M_{H2PV}= 2873944/119.95 * 10^3 = 24 kg of H_2/ month

Minimum M_{H2PV}= 293064/119.95 * 10^3 = 2.5 kg of H_2/month

Similarly, we can calculate hydrogen production of wind turbine as

$M_{H2WT} = E_{H2WT}/LHV_{H2}$, M_{H2WT} = 972/119.95 =8.1 kg of H_2/month.

3.5.2.3 Calculation of technical potential

After testing the theoretical potential of the regional wind and solar data, the next step is to evaluate the technical potential of H_2 from commercially available wind turbines and solar PVs.

Following the Sissons et al. (2011) paper, the technical potential of wind turbines is calculated and is shown in the table and graph below:

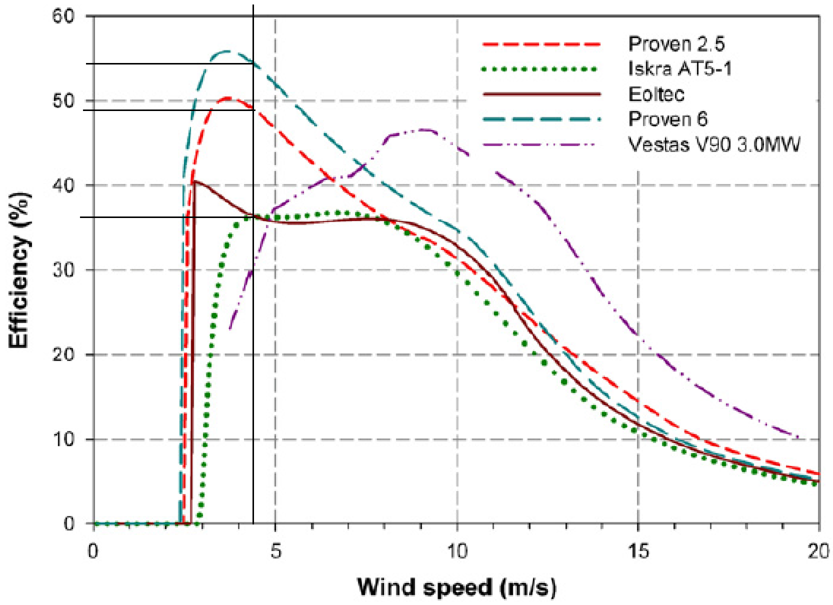

Figure2: Efficiencies of some commercially available micro-wind turbines as function of wind speed. Adapted from (Sissons et al., 2011).

Table 22: Specifications of different types of wind turbines.

	Eoltec Scirocco	Iskra AT5-1	Proven 2.5	Proven 6
Swept Area (m^2)	24.6	22.9	9.6	23.8
Diameter (m)	5.6	5.4	3.5	5.5
Efficiency η_{WT}	0.37	0.37	0.49	0.54

Efficiencies of the wind turbines are read from the figure2. Modification of equation 4 with multiplication of efficiency η_{WT} is now suitable to calculate the technical potential of wind. Then the results of one year total are shown in Table 23 below:

Table 23: Potential power outputs of different types of wind turbines.

	Eoltec Scirocco	Iskra AT5-1	Proven 2.5	Proven 6
1 WT (kW/year)	5.651	5.260	2.920	7.979

Solar data is crucial part of the project. There is plenty of work on photovoltaic solar cells in literature. Four photovoltaic cells are selected based on their efficiency, one for average efficiency, one for maximum efficiency and two in between (Green, Emery, Hishikawa, Warta, & Dunlop, 2011) and photovoltaic efficiencies are shown in Table 47 below:

Table 24: Efficiencies of different types of photovoltaic.

	Si (crystalline)	GaAs	CIGS	GaInP/GaInAs/Ge
Efficiency η_{PV}	0.25	0.283	0.174	0.341

By using MetOffice data and the efficiencies above, calculation of technical potential of photovoltaic is executed. The results shown on Table 25 are high as expected.

Table 25: Potential Power outputs of different types of Photovoltaic.

	Si(crystalline)	GaAs	CIGS	GaInP/GaInAs/Ge
$1m^2$ PV (kW/year)	1.909	2.161	1.329	2.604

With respect to the power production data for both wind turbine and solar photovoltaic, it can be concluded that using photovoltaic would be more efficient and productive choice.

Technical potential of hydrogen production is calculated after using equation 6 given in Dagdougui, Ouammi, and Sacile (2011). Same assumptions are made with the latter paper as: electrolyser operates at 75% efficiency (η_1) and the loss is 0.9 (η_2). Under this circumstances the maximum production of each component shown on Table 26:

Table 26: Yearly kg H_2 production of different renewable energy components.

Hydrogen Production kg (per hour per WT)			
Eoltec Scirocco	Iskra AT5-1	Proven 2.5	Proven 6
0.11447353	0.106563	0.059161	0.161636322
Hydrogen Production kg (per hour per $1m^2$)			
Si(cryst)	GaAs (thin Film)	CIGS	GaInP/GaInAs/Ge
0.038669293	0.043774	0.026914	0.052744916

As it can be seen on the table above, the most productive components are Proven 6 and multi-junction photovoltaic, and the least ones are Proven 2.5 and CIGS.

Yearly production is also considered and shown on the following figures, based on one micro wind turbine and one m^2 solar cell.

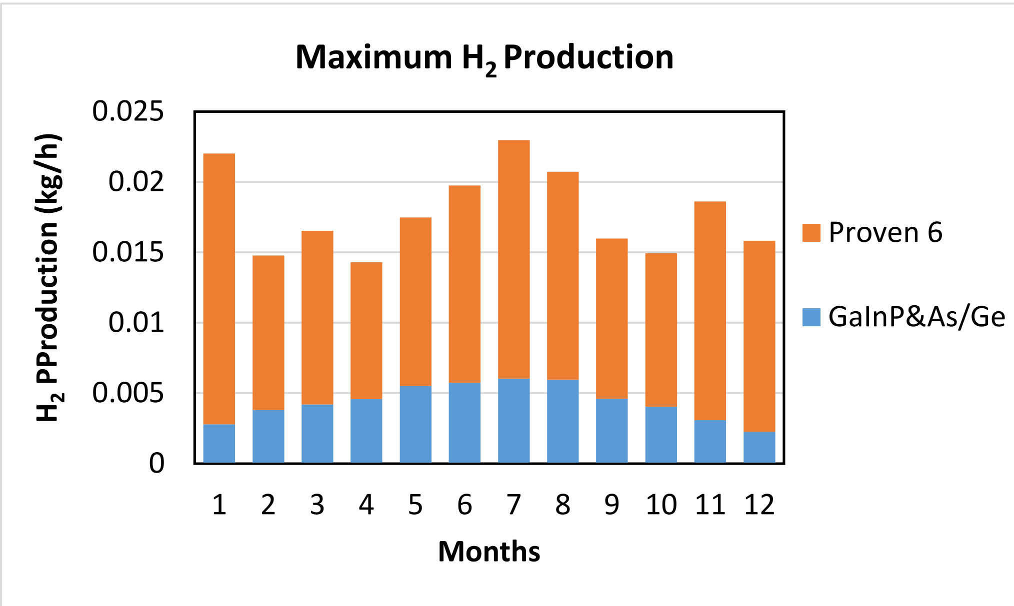

Figure 67: Monthly maximum H_2 production with the most productive components.

As shown in Figure 67, the maximum production with the most productive components is on July as 0.023026954 kg/h and the minimum is on December as 0.015850826 kg/h as expected.

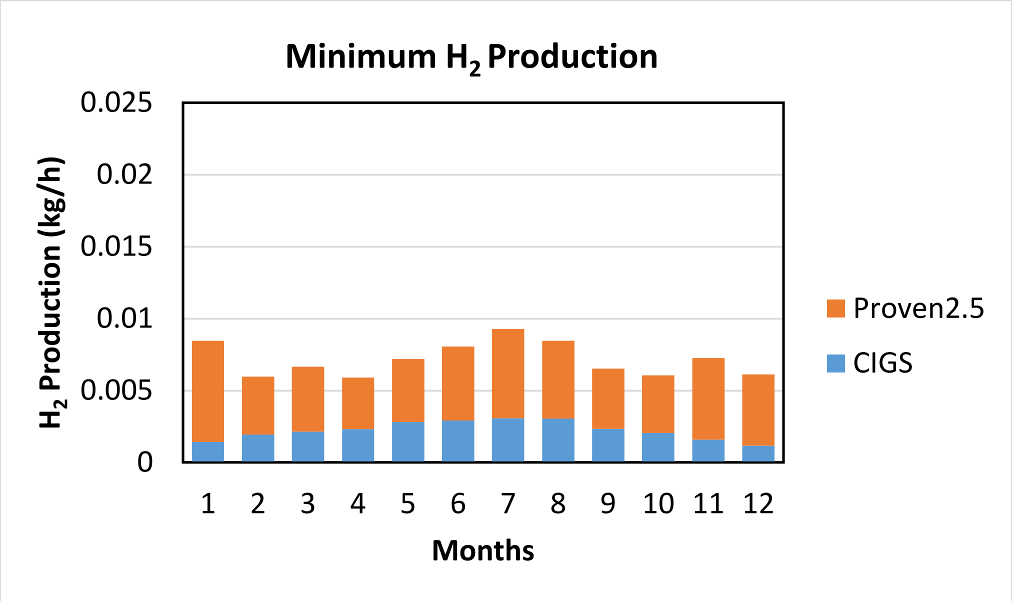

Figure 68: Monthly minimum H_2 production with the least productive components.

As shown in Figure 68, the maximum production with the least productive components is on July as 0.0093 kg/h and the minimum is on December as 0.0061 kg/h as expected.

The two points should be considered with respect to the figures above.

- The trend of production of hydrogen due to solar and wind power is the same and closely follows the trend of monthly averaged solar radiation and wind speed data.
- The production bars only shows one wind turbine versus one m^2 solar cell, however, if efficiency and the area usage is integrated into the evaluation, it is obvious that solar panels are more effective.

3.5.3 Annual energy requirement for hydrogen production

3.5.3.1 Bus route analysis

Here on, the analysis of bus routes interpreted towards our aim to cover U1 and HydroLink. Based on time tables provided by Uni-Link, U1 is working in a

12km one trip distance, 89 times for each weekday, 66 times for Saturdays and 56 times for Sundays[27]. Hence, all our buses on this route are going to cover a total distance of 707616 km/year. Same frequency pattern is assumed for HydroLink ring service as seen on the map (Figure 69). The distance of the ring route is 7.8 km, therefore total distance would be 459950.4km/year.

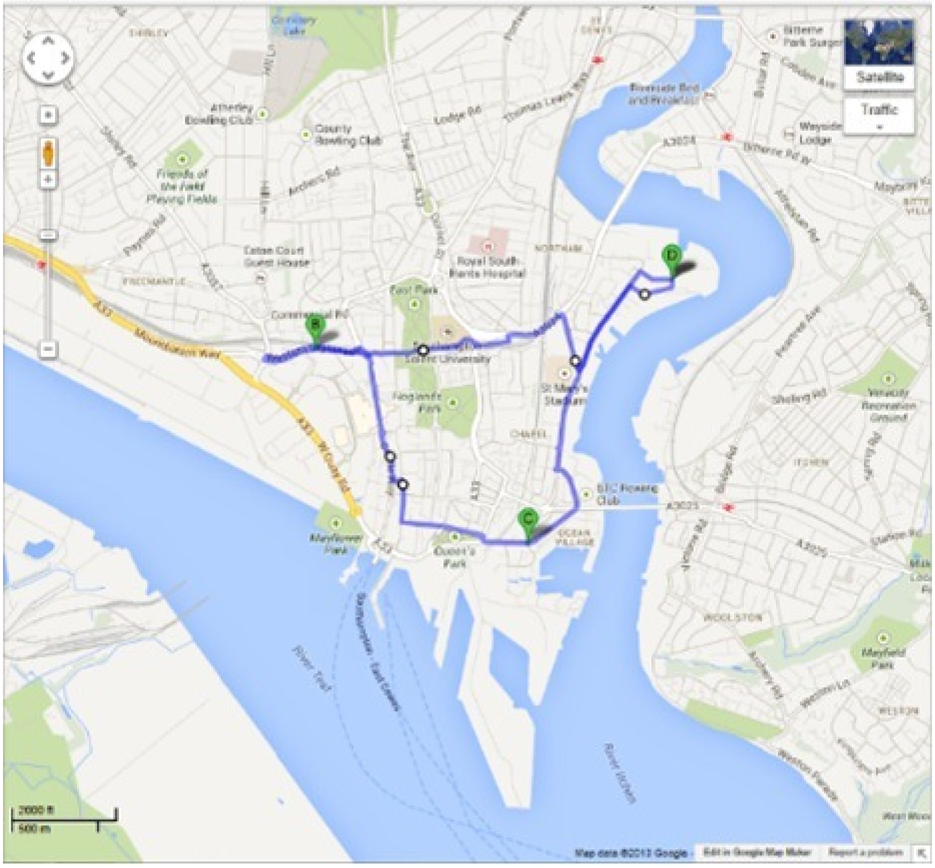

Figure 69: HydroLink route map.

Using the technical specifications of existing commercially available buses, the estimated maximum and the minimum fuel consumptions is 14 kg H_2/100km and 8 kg H_2/100km. The total distance covered with buses in these routes is 1167566km. Based on distance covered the maximum and minimum hydrogen need per year is calculated to be 163459.3kg H_2/year and 93405.3 kg H_2/year.

The hydrogen need of ferries is also calculated. Following the first law of thermodynamics and manipulation of the formulation of hydrogen mass

[27] Source: www.unilinkbus.co.uk.

production (ṁ) from Dagdougui et al(Dagdougui, Ouammi, & Sacile, 2011), the hydrogen consumption was calculated (3.8) where the power output of the ferry (P) over lover heating value (LHV) of hydrogen and the efficiencies of fuel cell (η_{FC}) and the electricity motor (η_{EM}). Hence consumption is

$$\dot{m}_{H_2} = \frac{P}{\eta_{FC}\eta_{EM}LHV_{H_2}}. \quad [kg/s] \qquad 3.8$$

The efficiency of the fuel cell is assumed to be 52% based technical specification on a commercial fuel cell (Proton Motor PM200), According to Mecrow and Jack (Mecrow & Jack, 2008), efficiency of electricity motor can be as high as 70%. According to the ferry design, about 5.62kW power is needed for it to sail. Mass flow rate or specific fuel consumption of one ferry is 1.674 10^{-4} kg/s which is 10.042 10^{-3} kg/min. There are six stops in the ferry route, the total distance and the total duration of sailing 4.0744km and 22.2 min. with the addition of stopping time at end-stops, total voyage time would be 44 min. that makes one round trip in 88 min. It is assumed that the ferries will work from 06:00 to 00:00 every day, i.e about 12 round trip are possible in a day. One ferry would therefore sail 44.4x12=532.8 min/day and 5328min/day for 10 ferries which is equivalent to 977.856 km/day. With respect to the fuel consumption calculated above, daily H_2 need for ten ferries is 53.504 kg/day. The yearly H_2 need is 19528.86 kg/year and total distance covered in one year is 356917.4km/year.

From the above information, our yearly need of H_2 production (HydroLink + U1 + Ferries) is 182988.161 kg/year for maximum, and 112934.177 kg/year for minimum conditions.

3.5.3.2 Hydrogen plant design

Given the promising hydrogen potential in Southampton as shown in Section 3.5.2.3, a H_2 plant is designed. The basic components of a H_2 production plant consist of filters, pumps, deionizers, electrolysers, compressors, coolers lastly storage tanks and more importantly, the area to build the plant. After research, and consultation with the city council officials the Ford Transit factory outside of the city next to Southampton Airport is chosen which is out of use for a while. The system to be modelled is a hydrogen power plant driven by a hybrid renewable energy system. The system is composed by a wind turbine, PV modules, electrolyser system and a hydrogen storage unit.

Figure 70: Ford factory area for the hydrogen plant[28].

The site covers a total area of 152171.95m^2 and is relatively flat area which also has short obstacles around the area which is important to consider for wind and solar power harvesting. Hence, efficient usage of this area for renewable energy is an important part. Efficient spacing of wind turbine is crucial due to blocking or giving highly turbulent wind to other wind turbines. According to (Patel, 2005), the gap between two wind turbines should be considered with respect to spacing and crosswind spacing, which he suggests 8-12 times more than the diameter and the latter is 2-4 times.

[28] Source: http://www.daftlogic.com/projects-google-maps-area-calculator-tool.htm.

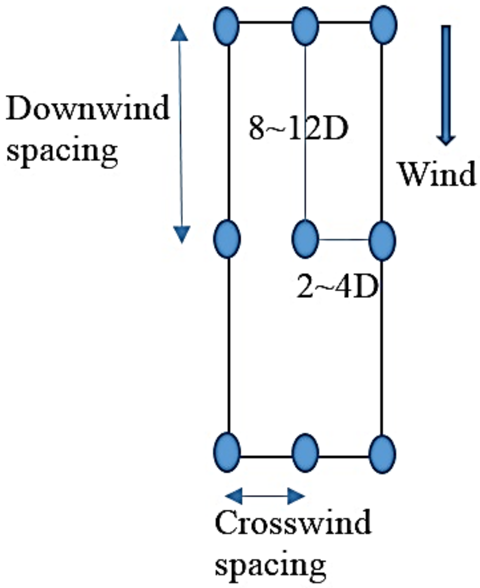

Figure 71: A sketch of WT siting.

Figure 71 shows the basic rectangular spacing of wind turbines. The area need for wind turbine for latter is 2 x 2D x 2 x 8D = $64D^2$ m^2. The chosen turbine has a diameter of 5.5 m^2, therefore area need for one micro wind turbine is 1936 m^2 and if all area is used for wind turbines we could build 78 of them, and gaps between them theoretically could be used for solar cells.

The energy potential of wind and solar sources has been previously shown (Section 3.5.2.3). Under the assumption of 6 hours of wind daily at around the average speed of 4m/s, total energy production from one micro wind turbine is calculated to be 1456 kWh/year. Therefore, in one year total energy production from 1 m^2 multi-junction photovoltaic can be approximately 374 kWh/year. Replacing the area of wind turbines with multi-junction photovoltaic panels actually 723994 kWh/year can be produced. Therefore, in comparison to wind turbines, photovoltaic seems to be approximately 500 times more productive in the same area.

In the H_2 production plant design the pump, deionizer and electrolyser sections are mainly considered as the core plant. Compressor, cooler and storage is considered as the part of fuelling station components as shown Figure 72.

The main component in a hydrogen plant is electrolyser. Besides the main components other components such as pump and deionizer and parameters such as energy demand, cost is considered in this study. This case study considers three of electrolysers, one of them corresponds the paper (Degiorgis, Santarelli, & Calì, 2007) which is Electrolyser 1 and the other two are commercially available electrolysers which are going to be mentioned as Electrolyser 2 and Electrolyser 3. Once main component selected the others are ready to design or select.

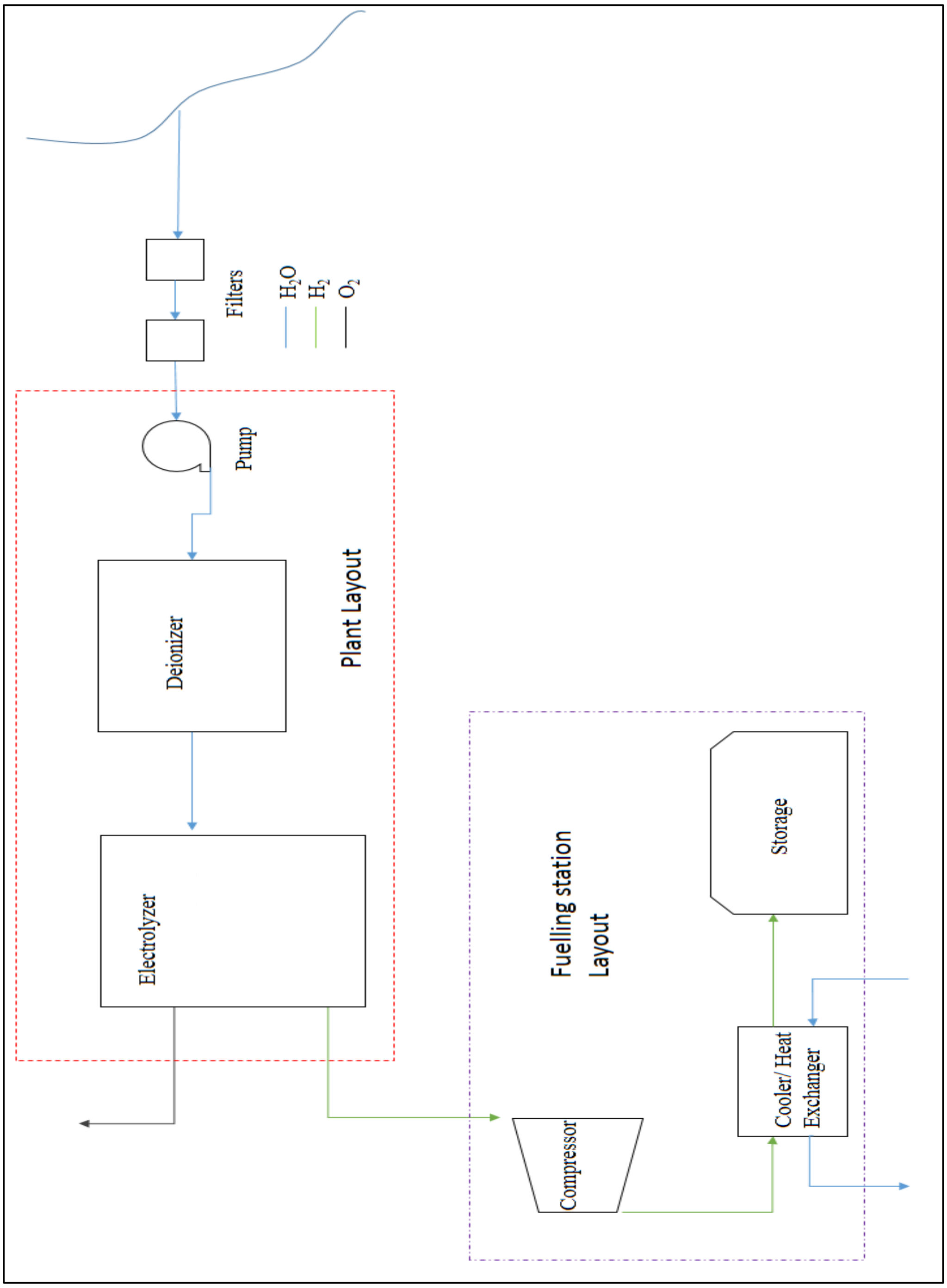

Figure 72: Plant and fuelling station layouts.

3.5.4 Annual energy requirement for hydrogen production

Yearly hydrogen need is known due to the fuel consumption of buses. Table 27 shows the required H_2 hourly production.

Table 27: Total hydrogen need in yearly and hourly bases.

Total H_2 need	kg/year	kg/h	Nm^3 / h
Maximum	182988.1608	20.88905945	232.4105413
Minimum	112934.1768	12.89202932	143.4360182

The next step is to know the energy need of production with respect to the components. Here only pump, deionizer and electrolyser into consideration. The pump is an important component for plant since it should procure the water need of the electrolyser. Water is assumed to be taken from River Itchen which is the closest water source only 908m (direct distance) from the plant. The pressure loss related to this distance is calculated using Darcy-Weisbach equation of pressure loss in pipelines with a little change after Cengel and Cimbala (Cengel & Cimbala, 2009):

$$\Delta P_L = f\frac{L}{D}\frac{\rho V_{avg}^2}{2} \quad [Pa] \tag{3.9}$$

Where f is Darcy-Weisbach friction factor, L length of the pipe, D diameter of pipe, V_{avg} average velocity of fluid, ρ is the density of the water. The pump compensates the pressure loss and pressurizes the liquid if it is required. In this case, there is no need to do the latter. The point to take into account is friction factor. It is only a function of Reynolds number (Re) which basically is the number to define flow characteristics (McKeon, Swanson, Zagarola, Donnelly, & Smits, 2004).

$$f = f(Re) \tag{3.10}$$

Where

$$Re = \frac{V_{avg}D}{\nu} \tag{3.11}$$

υ is the kinematic viscosity of the fluid. We improve the pressure drop equation into the power drop by

$$P_{pump} = \Delta P_L \frac{\dot{m}}{\rho} \quad [W] \tag{3.12}$$

where

$$\dot{m} = \rho\pi \frac{D^2}{4} V_{avg} \qquad \left[{}^{kg}/_{s}\right] \qquad 3.13$$

By using the equations, the pressure drop and power drop is calculated with respect to the selected electrolysers. Due to lack of technical specifications on the paper (Degiorgis et al., 2007), two commercial electrolysers, Electrolyser 2 and Electrolyser 3 is evaluated. The water consumption of both electrolysers, water mass flow rate is found to be as 1.2912 10^{-4} m^3/s for Electrolyser 2 and 5.7887 10^{-5} m^3/s for Electrolyser 3. Average velocity is assumed as 5m/s in each case. The optimum pipe diameter with these conditions is found to be 0.18133m (7in) for Electrolyser 2 and 0.1214m (5in) for Electrolyser 3. Kinematic viscosity is taken from ITTC viscosity tables as 1.30641 10^{-6} m^2s (refer to Appendix). Re numbers are found for each case as 693675.14 for Electrolyser 2 and 464468 for Electrolyser 3. The friction factor is determined and interpolated from the table (McKeon et al., 2004) to be 0.021846 and 0.01365 for the latter. Finally, pressure changes and power drops are found to be 0.80407 Pa and 0.10382 W for Electrolyser 2; 1.2706 Pa and 0.07387 W for Electrolyser 3.

Table 28: Results of pump specifications and needs.

	Electrolyser 2	Electrolyser 3
Re	693675.1431	464468.9081
f	0.012845779	0.01365
Pressure (Pa)	0.804071387	1.276045859
Power (W)	0.103819259	0.073867029

In conclusion, Table 28 shows that pump power is relatively small in comparison with the other components and hence it is negligible.

Deionizer is another important part of the plant because of the necessary to deionized water before it can be by the electrolysers. A continuous electro deionizer (CEDI) is chosen, which uses approximately 0.25 kWh to deionize 1 m^3 of water (Wood, Gifford, Arba, & Shaw, 2010). The table below shows the energy need of deionizer for each electrolyser's water consumption related to maximum and minimum bus needs.

Table 29: Energy consumption of deionizer for different cases.

Maximum Deionizer Energy Consumption (kWh/h)			Minimum Deionizer Energy Consumption (kWh/h)		
Electrolyser 1	Electrolyser 2	Electrolyser 3	Electrolyser 1	Electrolyser 2	Electrolyser 3
0.116	0.116	0.052	0.072	0.116	0.032

The vital part of plant with respect to the electrolyser has the energy consumption as shown in Table 30:

Table 30: Energy consumption of electrolysers for different cases.

		Maximum	Minimum
Electrolyser	Energy Consumption (kWh/Nm^3)	Energy Consumption (kWh/h)	Energy Consumption (kWh/h)
Electrolyser 1	4.09	950.559114	586.6533144
Electrolyser 2	4.9	1138.811652	702.8364892
Electrolyser 3	5.8	1347.98114	831.9289056

The reason for unit kWh/h is not written as kW is the need of further calculation on yearly energy consumption as kWh/year.

In conclusion, total yearly energy demand to produce required hydrogen in this three H_2 plants is listed in Table 31:

Table 31: Total yearly energy consumption for each case of H_2 plants.

	Maximum	Minimum
Plant with	Total Energy Consumption (kWh/year)	Total Energy Consumption (kWh/year)
Electrolyser 1	8327915.796	5139711.284
Electrolyser 2	9977008.033	6157475.895
Electrolyser 3	11808314.78	7287697.213

An assumption is made in this table is that the plant is working 24 hours a day and 365 days in a year. The nonstop working might result serious fatigue damages on components, nevertheless it is a logical assumption as a start.

To find the best way to produce energy, two simple scenarios are considered, 1. Using only photovoltaic and 2 using only wind turbines. Results shows photovoltaic are the best way to produce energy for the region. These values are stationary and change only with wind turbine and photovoltaic specifications. Results are given in Table 32:

Table 32: Maximum energy harvested from all factory area due to PV and WT.

	Max production (kWh/year)
Photovoltaic	56906840.17
Micro Wind Turbine	113577.0042

However, there will be times after sun sets or cloudy sky, wind turbines can be used to keep photovoltaic on standby mode with the energy they generate. Depending upon the information given, an area optimization is considered. That is, how many of micro wind turbines and photovoltaic panels is needed if they cover the same amount of area. Results are shown on Table 33:

Table 33: Area equality between WT and PV for each case.

	Maximum		Minimum	
	No of WT	Area of PV (m^2)	No of WT	Area of PV (m^2)
Electrolyser 1	11	22227	7	13717
Electrolyser 2	14	26625	8	16434
Electrolyser 3	16	31514	10	19449

Therefore, the results of this shows that by constructing a hydrogen plant fed by renewable resources (wind and solar) the energy requirement and the hydrogen production demand can be meet. The production capacity of the plant is actually more than the current requirement for the proposed transport services. This proves that the plant can be sustainable as well as independent from the grid and has the potential to meet additional demands future.

The next section and probably the most sensitive part deals with cost analysis of power plant. This section is to understand the feasibility of the project in the lines of energy and the production demand.

3.5.5 Analysis of hydrogen production cost via suggested hydrogen plant

In order to perform the cost analysis net present value method is chosen which is also suggested by paper (Ajanovic, 2008). The structure of cost analysis is built based on maximum and minimum demand of hydrogen as well as different types of electrolysers and concentrated multi-junction photovoltaic.

For any system, the total investment cost includes the sum of all direct and indirect costs. Direct cost is the price of main equipment’s while the latter is operating and maintenance etc. The individual costs are taken from market research and some assumptions are made with respect to paper (Ajanovic, 2008).

Following Ajanovic (2008), the cost of hydrogen C_{H2} is calculated according to the following equation:

$$C_{H_2} = \frac{\sum_{j=1}^{n} IC_j CRF_j}{Q} + \sum_{j=1}^{n} C_{B_j} \quad \left[{}^{£}/_{kg}\right] \qquad 3.14$$

where Q is quantity of hydrogen (kg H_2/year), IC_j are investment costs of module j (£), C_{Bj} are operating costs (£/kg H_2) and CRF is capital recovering factor and CRF equation is given as below (Bejan, Tsatsaronis, & Moran, 1996):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad 3.15$$

where *i* is interest rate, n is the life time of the component (year). According to the book (Bejan et al., 1996), multiplication of IC_j with CRF_j gives annual value of investment cost based on the life time of the component (A). Hence the equation above is:

$$C_{H_2} = \frac{\sum_{j=1}^{n} A_j}{Q} + \sum_{j=1}^{n} C_{B_j} \quad \left[{}^{£}/_{kg}\right] \qquad 3.16$$

where $A_j = IC_j CRF_j$

Additional operating costs are also given in Ajanovic (2008) and is modified slightly to make them applicable for the present study is given below:

$$C_B = \frac{C_{BF} + C_{BS}}{Q} \qquad 3.17$$

where C_{BF} are fixed operation costs (£/year), C_{BS} are other variable operational costs (£/year).

The costs of energy services (mobility or service cost) is calculated as (Ajanovic, 2008):

$$C_S = \frac{C_C}{S} + C_{H_2} sfc \quad \left[{}^{£}/_{km}\right] \qquad 3.18$$

where C_C is annual payment of capital costs of the end use conversion technology upon lifetime (£/year), S is the service demand (driven km/year), sfc is specific fuel consumption (kg H_2/km).

To execute and evaluate cost analysis, the fixed operating costs is estimated as 5% and the variable costs is considered as 1% of the total capital cost. Average interest rate is taken as 6.5% and fuel cell lifetime is 10 years (Ajanovic, 2008).

Lifetime of PV is taken as 25 years (Kinsey et al., 2008). According to study by Cotal et al. (2009) a multi-junction cells of 37% efficiency cost between \$8 and \$10/cm^2 in large quantities. A different study by Sherif et al. (2005) shows that \$10/cm^2 cell with 35% has a system cost of \$2/W. Recently, R. R. King demonstrated that a 500X point-focus concentrated 35% efficient multi-junction cells cost ranges from \$3-10/cm^2, while the system cost ranged \$1.2-2/W (King, 2009). He further demonstrated that cost of a 600X point-focus concentrated multi-junction cells with 35% efficiency ranged from \$5-10/cm^2 and system cost ranged between \$2-2.5/W (Kinsey et al., 2008). R For this U.S. dollars amounts were converted to British Pound Sterling for cost analysis.

The same lifetime of photovoltaic is assumed for micro wind turbine. A fully installed (including ground works, foundations, electrical and mechanical works, commissioning etc.) micro wind turbine would range between £25000 and £30000 in the UK (the value provided by a producer). Finally, for Electrolyser 2 the capital cost for size level is scaled using the equation below modified after Saur (2008).

$$y = 145918.5x^{0.6156} \quad [£] \qquad 3.19$$

where y equals the capital cost of the electrolyser (£) and x equals kg H_2/hr.

The capital cost of deionizer is assumed as \$10000 after market search.

Lastly, the estimated cost of a transportation fuel cell system is \$51/kW (Inc Breakthrough Technologies Institute, 2011). The currency change necessity shows up during data process between British Pound Sterling and US dollars and currency rate is taken as below:

$$\$1 = 0.645369£ \quad 3.20$$

For cost analysis, three criteria are considered: maximum and minimum demand of hydrogen, maximum minimum values of wind turbine and photovoltaic and finally the concentration of photovoltaic. Also one more necessary thing to mention is in order to evaluate service cost analysis we made an assumption that Uni-link U1 bus route have 15 and HydroLink route have 8 buses.

For the first case, the maximum hydrogen demand with 600X concentrated photovoltaic is considered; this case is shown in tables below.

Table 34: Maximum hydrogen and renewable device demand.

Q(kg/year)	Number of WT	Area of PV (m^2)
182988.1608	12	26632.33109

To produce Q amount of energy and some other need, 12 wind turbines and to compensate the remaining need PVs are calculated.

Table 35: Investment cost intervals of WT and PV.

	Investment cost min	Investment cost max
1 WT (£)	25000	30000
1 m^2 PV (£)	384.4259815	480.502632

As mentioned in the text above, costs are put in Table 35. To calculate the cost of 1 m^2 PV, the maximum power output of PV is used. From now on, one wind turbine value will not be included in the tables below, because it always has the same cost interval.

Table 36: Operation costs and their components for each sub case.

		min	max
WT (£/year)	C_{BF}	1229.722216	1475.66666
	C_{BS}	245.9444433	295.1333319
PV (£/year)	C_{BF}	41966.97609	52455.46201
	C_{BS}	8393.395219	10491.0924
WT (£/year)	C_B	0.008064274	0.009677129
PV (£/year)	C_B	0.275211091	0.343992497

C_B values are calculated for WT and PV as shown in Table 36 above.

Table 37: Other mentioned components and their values for calculation.

Components	Values
CRF	0.081981481
IC of electrolysers (£)	947659.7229
IC of Deionizer (£)	6453.69
C_B electrolyser (£/year)	0.025473959
C_B deionizer (£/year)	0.000173481
C_C: A bus(£/year)	26395.11494
C_C: A Ferry (£/year)	335.4486
S bus (km/year)	1167566.4
S ferry (km/year)	356917.4
Fuel Cell (£/kW)	33
one bus(kW)	250
One ferry (kW)	7.307525
1bus FC value (£)	8250
1 ferry value (£)	241.1483
total buses amount (£)	189750
Total ferries amount (£)	2411.483
sfc of bus kg/1km	0.14
sfc of ferry kg/1km	0.054715

The other important components of the cost analysis are as listed in Table 37. This table includes initial costs, C_B, fuel cell etc. Some of these values are always same for maximum and minimum hydrogen production, hence they are omitted in future tables.

Table 38: First case results on costs.

	Min	max
C_{H2} (£/kg)	5.457636212	6.701268164
Bus C_S (£/km)	0.786676019	0.960784493
Ferry C_S (£/km)	0.299556	0.367602

The result table shown above includes service cost of ferries and busses as well as hydrogen production cost in the plant's lifetime.

For the second case minimum hydrogen demand with 600X concentrated photovoltaic are shown in the following tables.

Table 39: Minimum hydrogen and renewable device demand.

Q(kg/year)	Number of WT	Area of PV (m^2)
112934.1768	8	16434.27173

Using a 600X concentrated PV, no change of the investment cost of 1 m^2 solar cell is observed.

Table 40: Operating costs for each sub case.

		min	max
WT	C_B	0.008711072	0.010453287
PV	C_B	0.275172364	0.343944092

The calculation results for C_B values for WT and PV are given in Table 40. Values of other components to execute the calculations are computed and given in Table 41.

Table 41: Other mentioned components and their values for calculation.

Components	Values
IC of electrolysers (£)	704083.4553
C_B electrolyser (£/year)	0.030666609
C_B deionizer (£/year)	0.000281093
C_C:A bus (£/year)	12669.65517
Fuel cell(£/kW)	33
one bus (kW)	120
total buses amount (£)	91080
sfc of bus kg/1km	0.08

Related to the information given above, cost results are found and given in Table 42.

Table 42: Second case results on costs.

	min	max
C_{H2} (£/kg)	5.562017	6.807763
Bus C_S (£/km)	0.455813	0.555472
Ferry C_S (£/km)	0.305268	0.373429

For the third case the maximum hydrogen demand with 500X concentrated photovoltaic, the number of wind turbine and the area need of photovoltaic is the same with the first case and is shown as tables below:

Table 43: Investment cost interval for PV.

	Investment cost min	investment cost max
1 m^2 PV (£)	230.7009531	384.4021056

The only change is on PV because where it changed from 600X into 500X photovoltaic.

Table 44: Operating costs for PV.

		min	max
PV (£/year)	C_B	0.165159131	0.275193998

All values that are not reported in Table 45 is the same with first case numbers as long as they are dependent on same variables.

Table 45: Third case results on costs.

	min	max
C_{H2} (£/kg)	3.513385	5.485828
C_S Bus (£/km)	0.514481	0.790623
C_S Ferry (£/km)	0.193176	0.301099

For the last case, minimum hydrogen demand with 500X concentrated photovoltaic is considered. Number of wind turbine and the photovoltaic area need is the same with second case as well as the other variables except investment cost of photovoltaic which is the same with third case. Hence the result table is shown below:

Table 46: Fourth case results on costs.

	min	max
CH_2 (£/kg)	3.618039	5.592494
C_S Bus(£/km)	0.300294	0.458251
C_S Ferry (£/km)	0.198902	0.306935

3.5.5.1 Variations in production and service cost with wind turbine usage area

Though throughout the study it has shown that PV has a better energy generation potential in the region in comparison to wind turbines, but the idea is to set up a hybrid (wind-solar) plant. Therefore the effect of wind turbines by its area coverage on the service and production cost is ascertained. Table 47 shows the total number of wind turbines and the % area covered.

Table 47: Area ratio of (WT/PV) change with No of WT.

No of WT	Area Ratio %(WT/PV)
0	0
2	23.5
4	47
6	70.6
8	94
9	106
17	200
78	934

In the table, 934% means that even all area used to plant wind turbines is not adequate to generate energy required by hydrogen production, hence it has to be used with PV.

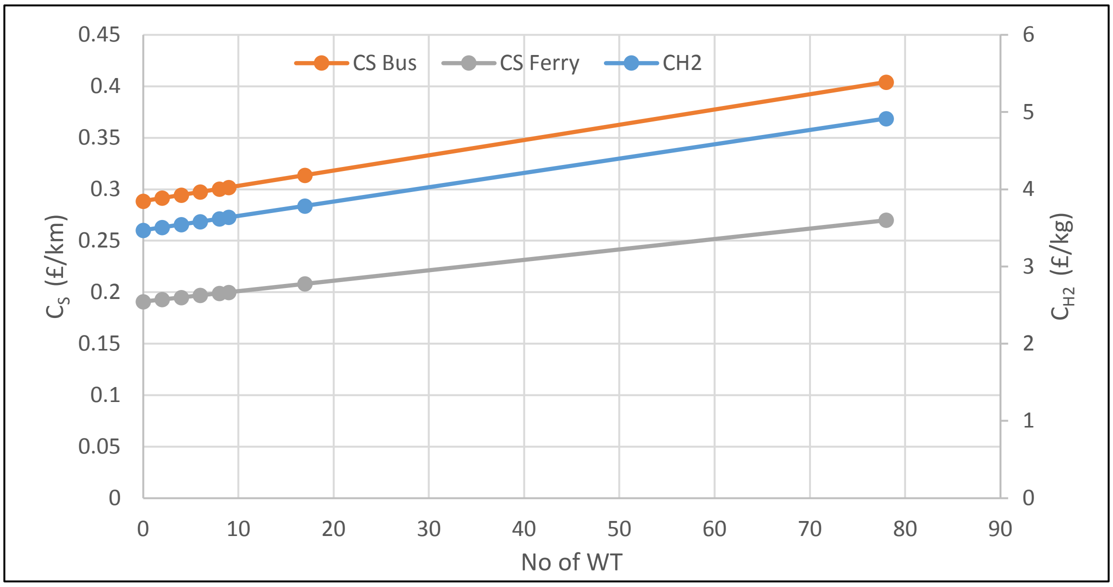

Figure 73: Change of hydrogen production cost and service costs due to number of wind turbines (WT).

Figure above shows that the minimum costs could be achieved without building wind turbines. In economical point of view, wind turbines should not be built. However to supply energy during standby mode of solar panels and keeping plant under working conditions wind turbines needs to be used.

3.5.5.2 Comparison to Diesel

A cost analysis is performed to understand the feasibility of using H_2 as an alternative to diesel under the present conditions.

Some assumptions were made to calculate the fuel consumption by ferry, the LHV_D is considered as 42.791 MJ/kg, efficiency (η_D) of diesel engine is 37% from common knowledge. Other data are ρ_D taken as 0.836633 kg/l, and lastly 1 litre diesel cost as £1.5 from the market research. With respect to these data, fuel consumption of a ferry is 0.150889 kg/km and market research shows the state of art technology diesel engine buses consume approximately 38.7 l/100km.

The amount of diesel fuel would be needed, if the services are U1, HydroLink and Ferries are on diesel engines. Results are shown in Table 48:

Table 48: Fuel consumption comparison.

	kg diesel/ year	min kg H_2/year	max kg H_2/year
U1, HydroLink and Ferries	431886	112934	182988

The fuel need of diesel engines is about 2.36 times beyond even maximum H_2 consumption.

In order to compare the hydrogen cost to diesel cost, the H_2 equivalent cost of diesel was calculated from the equation below:

$$C_{D,H_2} = \frac{LHV_{H_2}}{LHV_D} C_D \qquad 3.21$$

where C_D is recent diesel cost (£/kg). Executing this equation gives C_{D,H_2} as 5.025787 £/kg which is our threshold on cost analysis as it can be seen on figure below, 3rd and 4th (see in Figure 74) case minimum values are below the threshold, they would be useful to choose. However the other cases are still competitive with small differences. To see the bigger picture we need to sort out the service cost comparison of the ferry and the bus:

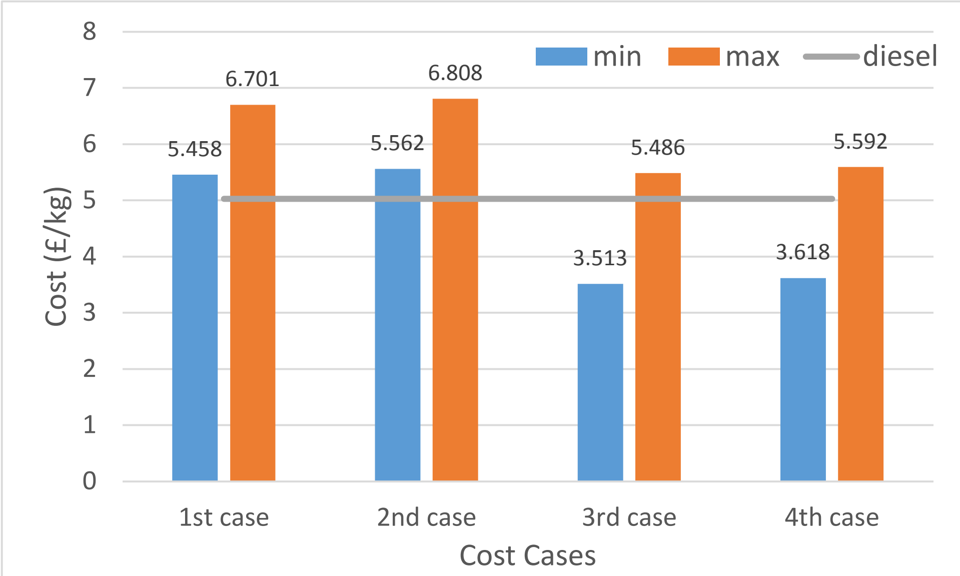

Figure 74: H_2 Cost Comparison with $\boldsymbol{C_{D,H_2}}$ Threshold.

In Figure 74, it is obvious that 2nd and 4th cases which have lower hydrogen production requirement (as given in Section 3.5.4) are more expensive than the other two. It is expected that higher mass production brings opportunity of lower cost in terms of production industry.

For service cost of bus, diesel threshold is calculated by multiplying C_D with fuel consumption which is $C_{S,Dbus}$ 0.5805 £/km. as it can be seen in Figure 75, 1st case is a little hard to be competitive however 2nd and 4th cases are suitable with being far less from threshold. 3rd case could be competitive.

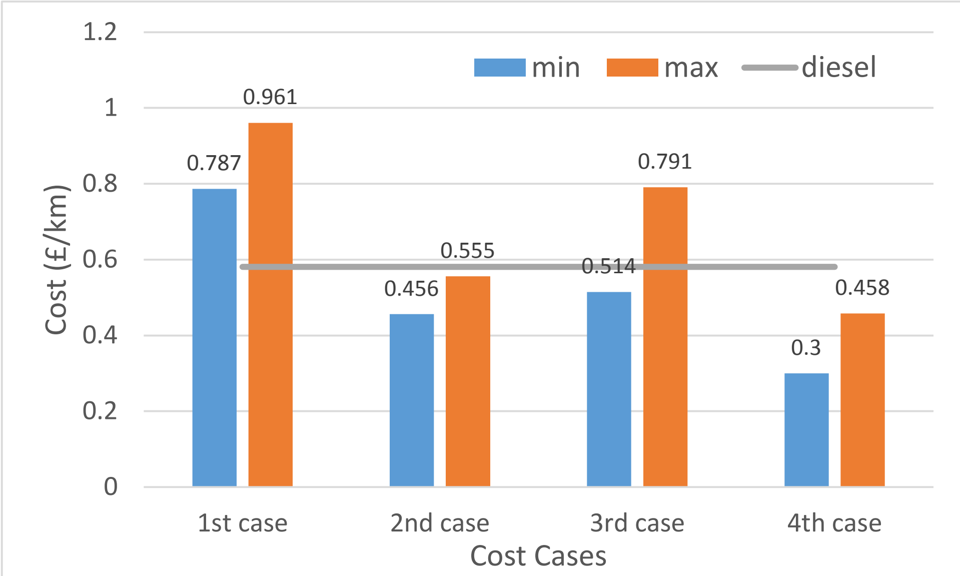

Figure 75: Service cost comparison with $C_{S,Dbus}$ threshold.

Referring to the calculated ferry fuel consumption, diesel service cost threshold is found to be 0.270528 £/km. according to Figure 76, all cases are competitive with respect to the ferry service cost.

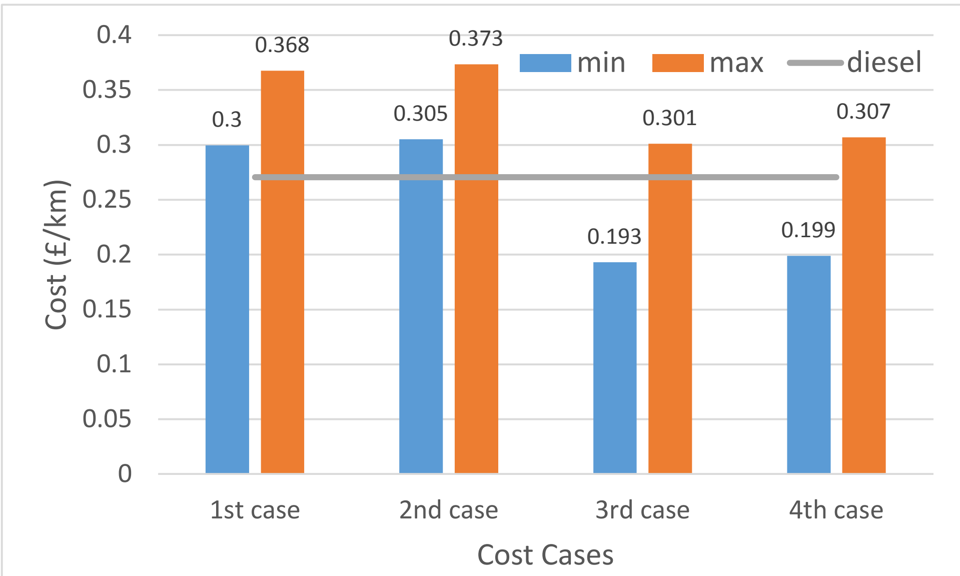

Figure 76: Service cost comparison with $C_{S,Dferry}$ threshold

Energy demand and cost analysis has been held in this part and it can be concluded that, 3rd and 4th (refer to Section 3.5.5.1) economic scenarios are be better choices and competitive with the diesel economy.

3.5.6 Carbon footprint analysis

Carbon footprint is an important tool to evaluate the impact of all processes on the environment. Nowadays, it is a popular term used in daily life and in scientific literature. There are several literatures that describe what carbon footprint but the term needs a universally accepted definition (Wright, Kemp, & Williams, 2011).

Carbon footprint can be defined as a measure of total amount of CO_2 emissions which is directly and indirectly created by any process (Wiedmann & Minx, 2007). Moreover carbon footprint is equal to the greenhouse gas emissions created by an individual, organization or product (Johnson, 2008). Furthermore, the carbon footprint of a process is the climate effect under a defined measurement that takes into account all related emissions sources, sinks, and storage in both consumption and production within the specified spatial and temporal system boundary (Peters, 2010).

The unit to compare the radiative forcing of greenhouse gases based on their global warming potential (GWP) is CO_2 equivalent, CO_2e (Ranganathan et al., 2004). GWP is an index to measure the radiative forcing of greenhouse gases in atmosphere over a chosen time horizon, usually 100 years. (Pachauri & Reisinger, 2007).

In this work Eco is defined as ecology as well as economy. Thus, an important aim of this study is reducing carbon footprint by introducing hydrogen buses and ferries. From the carbon footprint analysis[29] by just covering U1 bus link with hydrogen buses saves 79 tonnes of CO_2e per year.

The technical potential of Ford Transit factory area is 56906839.8 kWh per year by mounting PV to the whole area. That could produce 1043727.53 kg H_2 per year. The table below shows, if this amount of hydrogen would be used on buses what will be the covered distance and saved CO_2e:

[29] Source: www.carbonfootprint.com.

Table 49: Potential carbon footprint savings due to all area with PV to produce H_2.

	min	max
Distance covered (km)	7455196.643	13046594
tonnes of CO_2e saved per year	832	1457

4 Conclusions

The research reported in this work explored eco-friendly transport options in the coastal city of Southampton.

In the present analysis potential of clean energy (from renewable resources) and zero carbon emission (introducing hydrogen as fuel) is estimated for Southampton. The study is based on three different aspects: availability of the renewable energy (wind and solar), annual energy requirements and cost analysis. Each analysis was useful to define opportunities and challenges for the development of hydrogen economy in the region: particularly the potential use of hydrogen for vehicular transportation.

4.1 Major outcomes of the study

- Southampton has a very high potential of hydrogen, when the application of the hybrid (wind-solar) hydrogen power plant is been considered. It appears from the study results that aggregating the wind and solar energy sources for hydrogen production purpose could lead to solutions in reducing carbon emission from public transportation in the region.
- The present estimation indicates that an important part of the vehicular transportation in Southampton could by powered by hydrogen generated in the region.
- The estimated service costs based on hydrogen production from wind and solar resources are within competitive ranges with that of traditional diesel based services. The promising results from this conceptual study can help envision future clean alternative solution for the city.
- One of the important highlight of this work has been that the energy generated from solar photovoltaic could alone support the entire hydrogen demand for the proposed integrated transport system plus the U1 services in the region.

- Another unique aspect of this work is the conceptualization and design of a water ferry service. The work presents a preliminary design of a ferry which can easily be upgraded to serve a larger domain.

4.2 Recommendation for future work

In depth analysis in the following sections should be performed to carry forward the intended development plan.

- High resolution weather data needs to be collected for energy potential calculations;
- Complete the design of the ferry;
- An idea of using water routes to transport in Southampton is recommended, under the limited time it was not possible to include that in the present study;
- Planning and designing of a hydrogen power barges for waste transport through the water ways may be considered in future;

To cover the social aspects regarding introduction of a hydrogen technology broad and diversified educational program is highly advised. This includes different programs for different groups of people:

- School children/young people school talks
- Mature citizens - seminars in the community during afternoon tea sessions
- Special training courses to be given for future staff of hydrogen plant, refuelling stations and ferry crew should be considered

Ideas to generate revenue for the project as well as make it more appealing to the public:

- Introduction of one unified urban card
- Application of different mobile phone applications (i.e. live timetable APPs,
- Promotional APPs that allow users to gain points for using hydro-link system etc.)

- Advertisements such as posters and flyers in selected locations.

Appendix

	ITTC – Recommended Procedures	7.5 - 02 01 - 03 Page 5 of 6	
INTERNATIONAL TOWING TANK CONFERENCE	Testing and Extrapolation Methods, General Density and Viscosity of Water	Effective Date 1999	Revision 00

TABLE 3

Values of Kinematic Viscosity for Fresh Water

Temperature in degrees Centigrade

ν in metric units of $\frac{m^2}{s}10^6$

°C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.	1.78661	1.18056	1.77450	1.76846	1.76246	1.75648	1.75054	1.74461	1.73871	1.73285
1.	1.72701	1.72121	1.71545	1.70972	1.70403	1.69836	1.69272	68710	1.68151	1.67594
2.	1.67040	1.66489	1.65940	1.65396	1.64855	1.64316	1.63780	1.63247	1.62717	1.62190
3.	1.61665	1.61142	1.60622	1.60105	1.59591	1.59079	1.58570	1.58063	1.57558	1.57057
4.	1.56557	1.56060	1.55566	1.55074	1.54585	1.54098	1.53613	1.53131	1.52651	1.52173
5.	1.51698	1.51225	1.50754	1.50286	1.49820	1.49356	1.48894	1.48435	1.47978	1.47523
6.	1.47070	1.46619	1.46172	1.45727	1.45285	1.44844	1.44405	1.43968	1.43533	1.43099
7.	1.42667	1.42238	1.41810	1.41386	1.40964	1.40543	1.40125	1.39709	1.39294	1.38882
8.	1.38471	1.38063	1.37656	1.37251	1.36848	1.36445	1.36045	1.35646	1.35249	1.34855
9.	1.34463	1.34073	1.33684	1.33298	1.32913	1.32530	1.32149	1.31769	1.31391	1.31015
10.	1.30641	1.30268	1.29897	1.29528	1.29160	1.28794	1.28430	1.28067	1.27706	1.27346
11.	1.26988	1.26612	1.26277	1.25924	1.25573	1.25223	1.24874	1.24527	1.24182	1.23838
12.	1.23495	1.23154	1.22815	1.22478	1.22143	1.21809	1.21477	1.21146	1.20816	1.20487
13.	1.20159	1.19832	1.19508	1.19184	1.18863	1.18543	1.18225	1.7908	1.17592	1.17278
14.	1.16964	1.16651	1.16340	1.16030	1.15721	1.15414	1.15109	1.14806	1.14503	1.14202
15.	1.13902	1.13603	1.13304	1.13007	1.12711	1.12417	1.12124	1.11832	1.11542	1.11254
16.	1.10966	1.10680	1.10395	1.10110	1.09828	1.09546	1.09265	1.08986	1.08708	1.08431
17.	1.08155	1.01880	1.07606	1.07334	1.07062	1.06792	1.06523	1.06254	1.05987	1.05721
18.	1.05456	1.05193	1.04930	1.04668	1.04407	1.04148	1.03889	1.03631	1.03315	1.03119
19.	1.02865	1.02611	1.02359	1.02107	1.01857	1.01607	1.01359	1.01111	1.00865	1.00619
20.	1.00374	1.00131	0.99888	0.99646	0.99405	0.99165	0.98927	0.98690	0.98454	0.98218
21.	0.97984	0.97750	0.97517	0.97285	0.97053	0.96822	0.96592	0.96363	0.96135	0.95908
22.	0.95682	0.95456	0.95231	0.95008	0.94786	0.94565	0.94345	0.94125	0:93906	0.93688
23.	0.93471	0.93255	0.93040	0.92825	0.92611	0.92397	0.92184	0.91971	0.91760	0.915149
24.	0.91340	0.91132	0.90924	0.90718	0.90512	0.90306	0.90102	0.89898	0.89695	0.89493
25.	0.89292	0.89090	0.88889	0.88689	0.88490	0.88291	0.88094	0.87697	0.87702	0.87507
26.	0.87313	0.87119	0.86926	0.86734	0.86543	0.86352	0.86162	0.85973	0.85784	0.85596
27.	0.854091	0.85222	0.85036	0.84851	0.84666	0.84482	0.84298	0.84116	0.83934	0.83752
28.	0.83572	0.83391	0.83212	0.83033	0.82855	0.82677	0.82500	0.82324	0:82148	0.81973
29.	0.81798	0.81625	0.81451	0.81279	0.81106	0.80935	0.80765	0.80596	0.80427	0.80258
30.	0.80091	0.79923	0.79755	0.79588	0.79422	0.79256	0.79090	0.78924	0.78757	0.78592

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